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Artifacts, Revolutionaries and Bureaucrats: The Sociotechnical Shaping of NASA's Space Shuttle

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Declaration

I declare that this thesis has been composed by myself alone from the result of my own research and any work that is not my own has been clearly referenced.

Brian Woods ______________________

Abstract

In Artifacts, Revolutionaries and Bureaucrats, I have combined oral accounts with primary and secondary documentation, to reconstruct a sociotechnical history of the National Aeronautic and Space Administration's (NASA's) space shuttle, from 1968 to 1985. Encompassed within the thesis is an exploration of the design, development, fabrication and operation of technology. Drawing from literature in the social studies of science and technology, the thesis aims to map the relations between the social and the technological and survey the underlying dynamics of technological change. A principal objective of this thesis is to show that the creation of technology is as much a social activity as a technical one: that social matters were as a significant influence on the content of the shuttle as technological or scientific matters. The thesis does not, however, neglect the role of the material world and also provides an analysis of the technical shaping of technology. Nevertheless, the aim of a historical sociology of technology is to reveal the error in assuming that technology is entirely under the control of rational decision making; that the process of technological change takes place along a well defined, sequential path; and that technological progress is inherently predictable. The practitioners of technology may strive to create order, system and control, but the history of technology is usually complex and contradictory.

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Contents

Chapter 1

Introduction

> ... history ought first of all to tell what happened and how. That, however, is little enough. From the very telling it ought to become clear why it happened thus and not otherwise.[1]

During antiquity, the retelling of an event held great prominence in historiography. The meaning, or "lesson"[2] of each event was illuminated through the occurrence, or the deed itself. Causality and context were not independent of an event, but revealed through it. Meaning in modern historiography, by contrast, is derived through causality; through an exposure of the underlying processes of history. Events are mere fragments of a story rather than the story itself.[3] Nevertheless, some events manage to retain their authority, impacting with such ferocity that they dominate the subject of study and bestow a meaning on its history. The explosion of the National Aeronautic and Space Administrations's (NASA's) space shuttle Challenger, on January 28, 1986, can be regarded as such an event. Since 1986, research into NASA's shuttle has primarily focused on

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1 Leon Trotsky, 'The History of the Russian Revolution,' E.W. Dupree (ed) ***The Russian Revolution*** (New York, Doubleday & Co. Inc., 1959), p viiii.

2 Throughout this text double quotation marks are used to indicate a contentious word or phrase, whereas single quotation marks denote a direct quote.

3 Hannah Arendt, 'The Concept of History: Ancient and Modern,' ***Between Past and Future: Eight Exercises in Political Thought*** (Middlesex, England, Penguin Books, 1993); Philip Abrams, ***Historical Sociology*** (Somerset, England, Open Books Publishing Ltd, 1982).

the failure of Challenger, examining both its causes and consequences.[4] In turn, many of these studies have created a starting point, a structure and a boundary within which the shuttle programme has been interpreted.

Notwithstanding the importance of Challenger, the event, nor the causes or consequences, are topics of this inquiry. Nor is it assumed that the shuttle's history was a straight line towards Challenger. Instead, the basic purpose of this thesis is to explore the creation of a large socio-technical assemblage: to chart the dynamics of that assemblage as it unfolds forward in time and to reveal the forces and dynamics that gave both the technology, and the social ensemble that formed around it, composition, function and utility. The central aim is to uncover the dynamics of and the relationships between, social and technological change. How do the social and the technological interact and what influence does each have on the other over time?

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4 For the definitive work on the Challenger accident see, Diane Vaughan, ***The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA*** (Chicago, The University of Chicago Press, 1996). Other academic examples include: John Logsdon, 'The Decision to Develop the Space Shuttle' ***Space Policy*** 2, (May, 1986), pp 103-119; John Logsdon, 'The Space Shuttle Program: A Policy Failure? ***Science*** (May 30, 1986), pp 1099-1105; Barbara Romzek, Melvin Dubnick, 'Accountability in the Public Sector: Lessons from the Challenger Tragedy,' ***Public Administration Review*** (May/June, 1987), pp 227-238; Jon Miller, 'The Challenger Accident and Public Opinion,' ***Space Policy*** (May, 1987), pp 122-140; Hans Mark, Larry Carver, 'Challenger and Chernobyl: Lessons and Reflections,' ***Interdisciplinary Science Reviews*** 12, (1987), pp 241-252; William Starbuck, Frances Milliken, 'Challenger: Fine-Tuning the Odds Until Something Breaks,' ***Journal of Management Studies*** 25, (July 1988), pp 319-340; Thomas Johnston, 'The Natural History of the Space Shuttle,' ***Technology in Society*** 10, (1988), pp 417-424; Randy Hirokawa, Dennis Gouran, Amy Martz, 'Understanding the Sources of Faulty Groups Decision Making: A Lesson from the Challenger Disaster,' ***Small Groups Behaviour*** 19, (November, 1988), pp 411-433; Alan Jarman, 'Context and Contingency in Public Sector Disaster Management: A Paths Model of the US Space Transportation System Failure, 1968-1988,' ***Journal of Contingencies and Crisis Management*** 2, (December, 1994), pp 191-204; Diane Vaughan, 'Autonomy, Interdependence, and Social Control: NASA and the Space Shuttle Challenger,' ***Administrative Science Quarterly*** 2, (June, 1990), pp 225-257; Claus Jensen, ***Contest For the Heavens: The Road to the Challenger Disaster*** Trans, Barbara Haveland, (London, Harvill Press, 1996). And two journalistic books on the subject are: Joseph Trento, ***Prescription for Disaster: From the Glory of Apollo to the Betrayal of the Shuttle*** (New York, Crown Publishers Inc, 1987); Malcolm McConnell, ***Challenger: A Major Malfunction*** (New York, Doubleday & Co, Inc., 1987).

The purpose of this chapter is to lay down some of the foundations upon which this thesis rests before the reader journeys through the labyrinth of events. An introduction to space, the shuttle and NASA is thus presented to inform the reader of the programmes current position and provide some background details. The main theoretical issues are then outlined so that the framework through which the data has been interpreted is made clear. A section on methods and sources follows; and, finally, the structure of the thesis is describe.

Space, the Shuttle and NASA.

Space has been a prominent issue on the United States (US) political agenda ever since the Soviet Union launched Sputnik I on October 4, 1957. From exploration to exploitation, the past forty years has seen an extensive build up of technological capabilities in space, especially in near earth orbit.[5] A whole host of artificial satellites are now in orbit; each carrying out their various functions while falling in ever decreasing circles towards the Earth. Their impact on methods of communication, information transferral, navigation, weather prediction, and both military and civilian surveillance, has been monumental. Space technology has also provided new forms of data and

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5 This build up has not just been the result of US activity. Many of the worlds most powerful nations have contributed to the construction of a sizable space infrastructure. Since 1957 there have been 3687 launches in the world, of which 1033 came from the US. NASA, ***NASA Pocket Statistics*** (Washington DC, NASA History Office, 1995), p B2.

improved methods for its collection for many scientific disciplines ranging from cosmology and astronomy to geography and biology. But without the means to access space, the utilization of this environment would be impossible. Thus, one of the most important elements in the space infrastructure, is the launch vehicle.

Conventionally, the method of escaping the Earths gravitational pull has been, and still is, the rocket: a ballistic or guided missile, that is entirely expendable; only the payload (cargo or spacecraft) being transported survives the journey. On January 5, 1972, President Richard Nixon announced that the US would invest in a multi-billion dollar enterprise to develop 'an entirely new type of space transportation system'.[6] Proclaimed as the "next logical step" from the Apollo Moon landing programme, the space shuttle was touted as a utilitarian space vehicle that would 'transform the space frontier and *revolutionize*' transportation to near Earth orbit.[7] The concept was to combine both aircraft and rocket technology to fabricate a reusable space transportation system, which would foster a new age of routine, safe, and economical space travel.[8]

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6 President Richard Nixon, ***Statement by the President***, Press Release from the Office of the White House Press Secretary, January 5, 1972 (National Air and Space Museum Archive, Washington DC).

7 ***Ibid.*** My emphasis.

8 The rhetoric surrounding the shuttle and its links to the opening up of a new space age can be found in a whole variety of publications and official documents. For some examples see: Wernher Von Braun, 'The Reusable Space Transport' ***American Scientist*** (November\December 1972), pp 730-738; Michael Collins, 'Orbiter is First Spacecraft Designed for Shuttle Runs,' ***Smithsonian*** (May, 1977), pp 39-47; John Yardley, 'To the First Launch,' ***Astronautics & Aeronautics*** (February, 1979), pp 28-34, 72; Jerry Grey, 'Implications of the Shuttle: Our Business in Space,' ***Technology Review*** (October, 1981), pp 34-46.

Yet, the shuttle's revolutionary impact has not been as widespread, nor as sweeping as the space industry's leading prophets foretold. It has not led to hotels in space, factories in orbit, bases on the Moon, nor any grand ships touring humans across the solar system.[9] Indeed, most of the satellites that are in orbit today were put there by conventional means, namely, the expendable rocket;[10] and NASA's control over the commercial space market has plummeted from a 100 per cent share in 1972, to 30 per cent in 1992.[11]

Beset with problems from its very conception, NASA's shuttle programme has endured many setbacks; the most prominent of which was the destruction of Challenger. Demands that the shuttle programme should be phased out, or replaced by the end of the century have come from some of the highest echelons of the US political system;[12] and the promise of a routine and economical means to access the Earth's orbit, remains a distant aspiration. Nevertheless,

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9 Such distant aspirations have long been part of the populist rhetoric on space and still serve to reinforce the direction of new space technology today. For examples see, Werhner Von Braun, 'Science Looks at Life in 2057 A.D.,' ***New York Times Magazine*** (December 8, 1957); Leonard David, 'To Boldly Go for Profit,' ***Scotland on Sunday*** (March 30, 1997).

10 Michael Skapinker, 'Upward Thrust is Restored,' ***Financial Times*** (November 13, 1997); Michael Skapinker, Ralph Atkins, 'Countdown to Success,' ***Financial Times*** (March 20, 1995); US Congress, Office of Technology Assessment, ***The Lower Tiers of the Space Transportation Industrial Base*** (Washington DC, US Government Printing Office, OTA-BP-ISS-161, August 1995); The National Research Council, ***From Earth to Orbit*** (Washington DC, National Academy Press, 1992).

11 In 1992 the European Space Agency, with its Ariane rockets, controlled 60 per cent of the commercial space market. See, G. Sojka, J. Mansfield, T. Dawson, ***Space Launch Oversight Trip: 23 August - 3 September, 1993*** (American Institute of Aeronautics and Astronautics Archive, Washington DC).

12 ***Report of the Advisory Committee on the Future of the US Space Program*** (Washington DC, US Government Printing Office, 1990).

over 25 years and $79 billion (1992 dollars) later,[13] the shuttle prevails as an operational vehicle and still finds justification through its links with the international space station.[14]

The past 25 years has also witnessed the decline of NASA. The dominant perception of the US space programme is that it is faltering. NASA, it has been argued, has ended up as an organization without direction; a fossilized, overcautious, and bureaucratic agency, that has lost its capacity for innovation and is no longer equipped to manage large complex technologies, nor able to argue credibly for a space policy on Capitol Hill.[15]

A Historical Sociology Of Technology.

Technology has often been treated as an autonomous thing. Derived only from its own "internal logic", or from the application of scientific knowledge. Within such a framework, technology only has "impacts", not contexts. It impinges on society from the "outside", shaping and

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13 Figure taken from R. Pielke, 'Space Shuttle Value Open to Interpretation,' ***Aviation Week and Space Technology*** (July 26, 1993), pp 57-58.

14 NASA, ***NASA Strategic Plan*** (Washington DC, NASA, February 1995); AIAA Public Policy Committee, ***America's Space Launch Capabilities***, February 1994 (American Institute of Aeronautics and Astronautics Archive, Washington DC); Kathy Sawyer, 'NASA Looks for Contractor to Move Shuttle Toward Privatization,' ***The Washington Post*** (June 7, 1995).

15 Albert Wheelon, 'A "Born Again" Space Program,' ***International Security*** 11, (Spring 1987), pp 142-150; Richard DalBello, 'Space Transportation and the Future of the US Space Program,' Radford Byerly, (ed) ***Space Policy Reconsidered*** (San Francisco, Westview Press, 1989); Riccardo Giacconi, 'Science and Technology Policy: Space Science Strategies for the 1990's,' Radford Byerly, (ed) ***Space Policy Reconsidered*** (San Francisco, Westview Press, 1989); Arthur Levine, 'The Future of the US Space Program: A Public Critique,' ***Public Administration Review*** 52, (March/April, 1992), pp 183-186; Howard McCurdy, 'NASA's Organizational Culture,' ***Public Administration Review*** 52, (March/April, 1992), pp 189-192; Henry Lambright, 'The Augustine Report, NASA, and the Leadership Problem,' ***Public Administration Review*** 52, (March/April, 1992), pp 192-195; David Callahan, 'Forks in Space,' ***Technology Review*** 96, (August/September, 1993), pp 60-67; Howard McCurdy, ***Inside NASA: High Technology and Organizational Change in the US Space Program*** (Baltimore, John Hopkins Press, 1993).

reshaping social order and social relations in its wake.[16] Society can do nothing, but learn how to adapt to the ever-changing, increasingly complex environment produced by technology.[17] Or, at worse, society is unable to keep pace with technological change and thus is consumed by it pervasive, rationally orientated nature.[18] In this framework technology is endowed with teleological tendencies; a rigid sequence of stages through which technological change *must* move in order to achieve some final state. This process is often equated with evolutionary progress, in the sense that the path of development will inevitably lead toward some "higher order of life". Such a perspective has led some to suggest, that once a technological design becomes established, incremental innovation will tend to follow a "natural trajectory".[19] And it has led others to conclude that once large technological systems get established their associated momentum becomes virtually unstoppable.[20]

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16 Wilbert Moore, (ed) ***Technology and Social Change*** (Chicago, Quadrangle Books, 1972); Robert Heilbroner, 'Do Machines Make History?' ***Technology and Culture*** (July, 1967), pp 335-345.

17 William F. Ogburn, ***On Culture and Social Change: Selected Papers*** O. Duncan, (ed) (Chicago, The University of Chicago Press, 1964).

18 Jacques Ellul, ***The Technological Society*** J Wilkinson, (trans) (New York, Alfred Knopf, 1964); Herbert Marcuse, ***One Dimensional Man: Studies in the Ideology of Advanced Industrial Society*** (London, Routledge & Kegan Paul Ltd, 1964).

19 Richard Nelson, Sydney Winter, 'In Search of a Useful Theory of Innovation,' ***Research Policy*** 6, (1977), pp 36-76; Giovanni Dosi, 'Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants of Technical Change,' ***Research Policy*** 11, (1982), pp 147-162; Giovanni Dosi, Christopher Freeman, Richard Nelson, Gerald Silverberg, Luc Soete, (ed) ***Technical Change and Economic Theory*** (London, Pinter Publishers, 1988).

20 David Collingridge, ***The Social Control of Technology*** (London, Francis Pinter Publishers Ltd, 1980); David Collingridge, ***The Management of Scale: Big Organizations, Big Decisions, Big Mistakes*** (London, Routledge, 1992).

However, the aim of a historical sociology of technology is to understand technology as a historical product and a social creation.[21] To reveal the error in assuming that technology is entirely under the control of rational decision making; that the process of technological change takes place along a well defined, sequential path; and that technological progress is inherently predictable. The practitioners of technology may strive to create order, system and control, but the history of technology is usually complex and contradictory.[22] Accordingly, this thesis follows other authors in the sociology of technology who have widened the boundaries of inquiry and treated scientific knowledge, technological artifacts and technological systems, as sociohistorical products.[23] Drawing from this wide field, the analysis aims to illustrate technology's diverse and unpredictable nature.

Hence, this reconstruction of the shuttle's history follows a broad "social constructivist" approach, and also draws heavily on systems and actor-network theories. The

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21 Donald MacKenzie, ***Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*** (Cambridge, Massachusetts, The MIT Press, 1993).

22 Thomas Hughes, ***American Genesis: A Century of Invention and Technological Enthusiasm 1870-1970*** (New York, Viking Penguin, 1989).

23 Writings in the social shaping of science and technology are numerous and varied. For background texts see, Barry Barnes, David Edge, (ed) ***Science in Context: Readings in the Sociology of Science*** (Milton Keynes, The Open University Press, 1982); Donald MacKenzie, Judy Wajcman, (ed) ***The Social Shaping of Technology: How the Refrigerator Got its Hum*** (Milton Keynes, Open University Press, 1985); Michel Callon, John Law, Arie. Rip, (ed) ***Mapping the Dynamics of Science and Technology: Sociology of Science in the Real World*** (London, MacMillian Press, 1986); Brian Elliott, (ed) ***Technology and Social Process*** (Edinburgh, Edinburgh University Press, 1988); Wiebe Bijker, Thomas Hughes, (ed) ***The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*** (Cambridge, Massachusetts, MIT Press, 1990); John Law, (ed) ***A Sociology of Monsters: Essays on Power, Technology and Domination*** (London, Routledge, 1991); Wiebe Bijker, John Law, (ed) ***Shaping Technology/Building Society: Studies in Sociotechnical Change*** (Cambridge Massachusetts, MIT Press, 1992); Robert Fox, (ed) ***Technological Change: Methods and Themes in the History of Technology*** (Netherlands, Harwood Academic Publishers, 1996).

common thread that ties these approaches together is a recognition that technologies are not created, nor employed, in isolation of political, economic, cultural and ideological interests; all play an active role in shaping the design and utility of technology. At their core, science and technology are social activities, created out of the interactions and negotiations between a large number of diverse actors and things. Thus, questions about design, development, fabrication and operation have to be framed to include both technical and societal matters. A historical sociology of technology has to open the "black box" of technology and expose its "inner workings".

The first methodological step in opening the black box is to locate and follow the "relevant actors".[24] Conventional wisdom has portrayed the inventor as the dominant actor in the story of technology. Locating the inventor or any "moment of invention", for a technology on the size and scale of the shuttle is, nonetheless, hindered by the very character of the machine. Forged from a myriad of different artifacts, all of which have their own micro-histories, the lineage of the shuttle can be traced back to several different people and various moments in time. NASA, of course, is the principal protagonist. It is the organization that set about to transform a two dimensional

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24 Trevor Pinch, 'The Social Construction of Technology: A Review,' Robert Fox, (ed) ***Technological Change*** pp 17-35; Wiebe Bijker, 'The Social Construction of Florescent Lighting, or How an Artifact was Invented in its Diffusion Stage,' Wiebe Bijker, John Law, (ed) ***Shaping Technology/Building Society*** chapter 3; Jane Summerton, 'Heroes, Giants and Critics: On Building Bridges Between Systems Approaches, ANT and STS,' (Paper for Actor Network and After Workshop, Keele University, 10-11 July, 1997).

concept into a three dimensional object. But, NASA itself is made up of nearly 30 000 people,[25] housed in ten separate field Centers, each with their own offices and directorates, and a headquarters. Working in alliance (and sometimes in opposition) to this complex organization are also actors within government, the state, the military, industry and academic organizations and institutions.

An appreciation of all these actors leads to the second methodological step, an acknowledgment that most modern technological artifacts are not self-contained things, but parts of much larger systems.[26] With technologies like the shuttle, there are a multitude of different actors that are linked together. So the formation and stabilization of these linkages form an important locus of the analysis. The shaping process cannot be understood without reference to the linkages and the technology's place within them. The definition and creation of an object is also the definition and creation of its sociotechnical context. Within such a context, the social and the technological are both at once created and transformed,

25 NASA direct employment has fluctuated over the years, from a peak of 35 860 in FY 1967 to 23 097 in FY 1994. NASA, ***Pocket Statistics*** (Washington DC, NASA History Office, 1995).

26 Thomas Hughes, ***Networks of Power: Electrification in Western Society*** (Baltimore, John Hopkins University Press, 1983).

each affecting the other in an on-going chain of events, unions and struggles.[27]

From here it is clear that the analysis must accommodate another important principle of the actor-network approach; namely, that the links between science, technology and society are so opaque that any attempt at separating them will be problematic. Society and technology are not seen as two ontological distinct entities, but as *phases* of the same essential action.[28] Distinctions between the social and the technical are argued to be problematic, because they can lead to the disproportionate selection of particular events for analysis. This may only exemplify mistakes or breakthroughs. Thus, sociologists should not concentrate their efforts on examining only the controversial or the successful, but should also focus on the "normal" and "everyday" activities of the "technologists".[29]

From this perspective it also becomes clear that a sociotechnical analysis has to treat the technology itself as an actor. In this study, this is principally the

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27 Michel Callon, 'Techno-economic Networks and Irreversibility,' John Law, (ed) ***A Sociology of Monsters***; Michel Callon, 'The Sociology of an Actor-Network: The Case of the Electric Vehicle,' Michel Callon, John Law, A Rip, (ed) ***Mapping the Dynamics of Science and Technology***; Michel Callon, 'The State and Technical Innovation: A Case Study of the Electric Vehicle in France,' ***Research Policy*** 9, (1980), pp 358-374; Bruno Latour, 'Technology is Society Made Durable,' John Law, (ed) ***A Sociology of Monsters***; Bruno Latour, ***Science in Action: How to Follow Scientists and Engineers Through Society*** (Milton Keynes, The Open University Press, 1987).

28 Bruno Latour, 'Technology is society made durable', John Law, (ed) ***A Sociology of Monsters*** p 129.

29 Bruno Latour, Steve Woolgar, ***Laboratory Life: The Social Construction of Scientific Facts*** (London, Sage Publications Ltd, 1979).

shuttle, but the shuttle is itself a system, constructed from tens of thousands of separate technologies. The focus of the analysis then, must not just be on the whole, but also on the parts of the shuttle. The inquiry thus follows the creation of particular sub-systems and aims to expose their influence on each other, on the gargantuan technological system and the wider sociotechnical network; all of which, in turn, dictated the shape of the sub-systems themselves. Uncovering the influence of *testing* on the configuration of sub-systems also forms an important part of the analysis of technological innovation. The role of the experiment in science has been widely investigated in the social studies of science, but there has been inadequate attention paid to technology's equivalent, the test. This analysis, therefore, goes beyond an exploration of how technology is shaped through the convergence and negotiations of different groups, to also show, through an inquiry into testing, how the actual technical workings are themselves embedded in social choices and negotiations.[30] The formulation of *predictions* about the operational environment, their influence on the construction of the tests, and the judgements made from the tests, are,

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30 Donald MacKenzie, 'From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy,' David Gooding, Trevor Pinch, Simon Shaffer, (ed) ***The Use of Experiments: Studies in the Natural Sciences*** (Cambridge, Cambridge University Press, 1989); Trevor Pinch, 'Testing - One, Two, Three, ... Testing: Towards a Sociology of Testing,' ***Science, Technology and Human Values*** 18 (Winter, 1993), pp 25-41; Walter Vincenti, ***What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*** (Baltimore, The John Hopkins Press, Paperback edition, 1993), especially chapter 5.

therefore, also explored and analyzed in relation to the shaping of sociotechnical assemblage.

Bruno Latour and Steve Woolgar have argued that the distinction between description and explanation is false: that if an analysis describes all that occurs then explanation will be self evident.[31] Although I would not venture this far, description is important to this historiography and the presentation of detail comprise a large part of the inquiry. Events are dissected to reveal their internal activities and agents. Milieus are surveyed to expose the mobilization strategies of their occupants, and various journeys are mapped to understand their impact on events. Detailed description is also applied to the technology and in parts this can be very dense. I make no apology for this. I believe that the history of a technology is empty without a study of the technological detail itself. Any research into technology *has* to make a commitment to understanding the technical issues. The role of the *material world* is a significant part of technological development and understanding how it shapes the composition, function and utility of technology, is fundamental. Relations between technologies, the physical environments within which they have to function, and the knowledge upon which they are based are important matters that need to be unpacked. A glossary has been provided and

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31 Bruno Latour, Steve Woolgar, ***Laboratory Life***; Bruno Latour, 'Technology is Society Made Durable,' John Law, (ed) ***A Sociology of Monsters***.

can be found in Appendix 1, if the reader feels in need of it.

However, opening the "black box" of technology is not an easy task. With a technology as complex as the shuttle, some black boxes must remain shut. Thus, in the narrative that follows, some decisions remain unexplained and there are many left unexplored.

It is not part of the analysis to make *judgements* about knowledge claims or competing technologies. The "good" or "bad", or the "right" or "wrong" way of doing things, is left to the statements made by the social actors involved in the programme. The narrative, therefore, employs what David Bloor has termed *symmetry*, what Donald MacKenzie had called *sociological relativism*, or what the sociology of technology now terms *interpretative flexibility*.[32] That is, a historical sociology of technology should treat "correct", "false" or alternative, claims, judgements and technologies, equally.[33] In any case, I do not have a background in rocket science,

32 David Bloor, ***Knowledge and Social Imagery*** (London, Routledge & Kegan Paul, 1976); Donald MacKenzie, 'Notes on the Science and Social Relations Debate,' ***Capital & Class*** 14 (Summer, 1981), pp 47-60; Wiebe Bijker, 'Do Not Despair: There is Life After Constructivism,' ***Science, Technology and Human Values*** (Winter 1993) pp 113-118; John Law, Michel Callon, 'The Life and Death of an Aircraft: A Network Analysis of Technical Change,' Wiede Bijker, John Law, (ed) ***Shaping Technology/Building Society*** pp 21-52; Wiebe Bijker, 'The Social Construction of Fluórescent Lighting, or How an Artifact was Invented in its Diffusion Stage,' Wiede Bijker, John Law, (ed) ***Shaping Technology/Building Society*** pp 74-102; Ronald Kline, Trevor Pinch, 'Users as Agents of Technological Change: The Social Construction of the Automobile in the United States,' ***Technology and Culture*** (October 1996), pp 763-795; Kann Garrety, 'Social Worlds, Actor-Networks and Controversy: The Case of Cholesterol, Dietary Fat and Heart Disease,' ***Social Studies of Science*** (October 1997), pp 727-73.

33 For a criticisms of this approach see, H. M. Collins, Steven Yearley, 'Epistemological Chicken,' Andrew Pickering (ed) ***Science as Practice and Culture*** (London, University of Chicago Press, 1992); Langdon Winner, 'Social Constructivism: Opening the Black Box and Finding it Empty,' ***Science as Culture*** 3 (1993), pp 427-451.

aeronautical engineering, nor any of the other numerous technical disciplines that converged to create the shuttle.

The emphasis of the systems and actor-network approaches on construction and agency has led to the criticism that it ignores or underplays the constraints placed on agents in their efforts to act.[34] The approach claims that there is no "inside" or "outside". That none of the heterogenous elements can be placed in a hierarchy, or can be distinguished according to their nature; each, so the argument goes, are as important as each other. In the absence of one ingredient the whole would breakdown. The existence of technology is bound up with the construction of the actor-world. Actors and structures are both "products", which are seen as created and sustained together.[35] Nevertheless, although technological systems are created out of multiple and diverse interconnecting parts, I do not agree with the idea that all of these parts are equal. The autonomy of people to act is *always* limited by the situations they are in.[36] Within each functioning sociotechnical system some parts are more crucial than

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34 For examples see, Langdon Winner, ***Ibid;*** Robin Williams, Stewart Russell, ***Opening the Black Box and Closing it Behind You*** (Edinburgh, PICT Working Paper No. 3, 1988); Stewart Russell, 'Response to Pinch and Bijker,' ***Social Studies of Science*** (May 1986), pp 331-46; Daniel Lee Kleinman, 'Untangling Context: Understanding a University Laboratory in the Commercial World,' ***Science, Technology, and Human Values*** (Summer, 1998), pp 285-314.

35 Michel Callon, 'Techno-economic networks and irreversibility', John Law J, (ed) ***A Sociology of Monsters*** p 137; Michel Callon, 'The Sociology of an Actor-Network: The Case of the Electric Vehicle,' Michel Callon, John Law, Arie. Rip, (ed) ***Mapping the Dynamics of Science and Technology***; Wiede Bijker, John Law, (ed) ***Shaping Technology/Building Society*** introduction; John Law, (ed) ***A Sociology of Monsters*** introduction.

36 V.I Allen, ***Social Analysis: A Marxist Critique and Alternative*** (Shipley, The Moor Press, 1975).

others. Some sections will be interdependent, while others will just be dependent. Hierarchical structures are a "normal" part of large human-machine networks. The centralization of control, although not always successful, is a pervasive aspect of the sociotechnical management of technological construction and operation.[37]

In addition, wider structural and historical conditions also determine the fate of technological systems. These conditions cannot just be seen as backdrops, or contexts. They play a vital role in shaping the possibilities and can even effect the content of the technology itself. Thus, the milieus of technological protagonists are located and analyzed in the structural and historical conditions within which they reside. Established relations and fixed boundaries existed simultaneously with emerging ones and their influence on the range of potentialities must also be explored. Detailed interaction is, therefore, blended with wider circumstances through an analysis of structural conditions, social action, and technological matters.

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37 Langdon Winner, ***Autonomous Technology: Technics-out-of-Control as a Theme in Political Thought*** (Cambridge, Massachusetts, The MIT Press, 1985), pp 181-185.

Sources and Methods.

A combination of oral accounts, primary and secondary documentation, was used to reconstruct a sociotechnical history of NASA's space shuttle. The majority of the data was collected from March to September 1995 on a field trip to the United States.

The documentary data:

Overall, 7 archives were accessed for the collection of documentary data: the NASA History Office, Washington DC; the Kennedy Space Center, Florida; the Marshall Space Flight Center, Alabama; the National Air and Space Museum, Washington DC; the American Institute of Aeronautics and Astronautics, Washington DC; the General Accounting Office, Washington DC; the National Academy of Science and Engineering, Washington DC. And 3 libraries at: the International Association of Machinists and Aerospace Workers, Maryland; the Space Policy Institute, George Washington University, Washington DC; and the University of Edinburgh, Edinburgh.

The History Office houses a sizable and diverse collection of sources that span a considerable number of years and cover a wide range of NASA's activities. The most significant collections to this study included: the Space Shuttle Historical collection; the LeRoy Day, Space Shuttle Historical collection; collections on NASA Administrators, Deputy Administrators, Associate Administrators of the Office of Manned Space Flight and the Office of Space

Flight; Directors of the Johnson Space Center, the Marshall Space Flight Center, and the Kennedy Space Center; and Congressional Hearings. But given the sheer breadth and depth of the sources available, other collections were also examined.

At the Kennedy Space Center archive the two principal collections explored were: the Kennedy Director, Kurt Debus collection and the G. Merritt Preston collection; although, many other files were also examined.

At the Marshall Space Flight Center archive time was mainly spent studying the shuttle historical collection, which is contained on microfilm. I scanned all available microfilms, noting documents of interest and Marshall then photocopied my selections and sent them on via mail at no cost.

At the National Air and Space Museum I was given hard copy catalogues of collections on NASA and the shuttle from which I selected certain files. Most of the collections specific to the shuttle and shuttle management were examined.

At the American Institute of Aeronautics and Astronautics (AIAA) I was allowed access to a computer database on AIAA publications and reports, from which I selected certain documents, which were then forwarded via mail at no cost.

At the General Accounting Office (GAO) Distribution Center, I used a computer database to locate reports on both NASA and the shuttle. The GAO photocopied every report requested, absolutely free of charge, and I would collect them a few days later. I also contacted the GAO Distribution Center on a number of occasion after my return to the UK and requested specific documents. Again these were photocopied and sent via mail at no cost.

The National Academy of Sciences and Engineering sent me reports, letters and other types of documentation requested via mail and at no cost.

The library at the International Association of Machinists and Aerospace Workers only contained a small collection on NASA, but there were a variety of other sources from which I could draw. Of significance was a complete collection of the union's paper, *The Machinist*, which proved a useful source in exploring the perspective of aerospace workers. A complete review of *The Machinist* (from 1969 to 1990) was, therefore, conducted.

The Library at the Space Policy Institute had small primary and secondary collection on NASA and the space shuttle, which was made full use of.

Finally, of course, I drew on the resources of the University of Edinburgh's own libraries. Significantly, the main library houses a complete collection of *Aviation Week and Space Technology*, which was donated by Faranti. Throughout the four years it took to complete this project, I made a complete review of *Aviation Week and Space Technology* (1968 to 1985).

The documentary data can be broken into the following types:

* Unpublished letters, memorandums, position papers, policy documents, technical reports, management instructions, management reviews and technical reviews, generated within and passed between, the NASA offices, Centers and the "outside world".

* Unpublished letters, memorandums, policy documents and technical reports, directed at NASA, but generated by other institutions, organizations and individuals.

* Letters sent to the author from those involved in the shuttle programme.

* Published letters, memorandums, technical documents, policy documents, management reviews and technical reviews, generated by NASA and other organizations, institutions and individuals.

* Congressional Hearings held in the Senate and the House on space policy, NASA budget authorizations and shuttle status.

* Conference papers written by engineers and bureaucrats from NASA and its contractors.

* Science and engineering professional, academic and news publications.

* Other professional, academic and "popular" publications.

* Press Releases from NASA, members of the White House and Congress.

* Clippings from newspapers, radio, television and the internet.

As well as primary sources, the thesis draws on a variety of secondary sources. However, in a historical project the distinction between secondary and primary is often blurred. Secondary sources are themselves locked into time. As such, an historical project can treat some of them as quasi-primary sources, because their content is shaped by their historical location and their sociohistorical context.

The coding of primary documents was an iterative process. At first I organized the data in chronological order. This was done for two reasons. First, whilst in the US it helped me locate gaps or particular issues that appeared throughout the period I was interested in. Second, when I arrived back in Edinburgh, the chronological order gave me an overall picture of the sequence of events and decisions made. The next step was to order the data into particular issues, subjects and topics.

Key issues, subjects and topics:

* External Politics: political issues/debates surrounding the shuttle from individuals, organizations and institutions outside of NASA. These files were also broken into the period blocks, which represented major phases in the shuttles's history: 1968-1972; 1973-1977; 1978-1981; and 1981-1985.

* Internal Politics: political issues/debates surrounding the shuttle from individuals, organizations and institutions inside NASA. These files were also broken into the period blocks, which represented major phases in the shuttles's history: 1968-1972; 1973-1977; 1978-1981; and 1981-1985.

* Budgetary Issues: issues/debates on costs of development both within and outside of NASA.

* Space Traffic Models and Cost-per-flight: issues/debates on the estimates of cost-per-flight, demand for the shuttle and space traffic models

* The Contractors: issues/debates about the role of the contractors, the selection process and the relationships between the contractors and NASA.

* Management and Organization: issues/debates on the management and organizational structures of the shuttle's development.

* Operations: issues/debates on the management and organizational structures of the shuttle's operations; and on the changing culture, practices and philosophies of shuttle operations as opposed to operations of external launch vehicles.

* Impact on the Kennedy Space Center: as above, only with focus on the Kennedy Space Center.

* The External Tank: design, development, fabrication and testing.

* The Thermal Protection System: design development, fabrication and testing.

* Aerodynamics and Aerothermodynamics: creation of models about environments and the design, development and fabrication of systems that they affected.

* The Space Shuttle's Main Engines: design, development, fabrication and testing.

* Booster Technology: design, development, fabrication and testing.

* The Orbital Manoeuvring System and the Reaction Control System: design.

* Atmospheric Flight: issues/debates on the role of air-breathing engines and on the selection of the carrier aircraft

Once the documentary data was separated, it was then reordered chronologically within its particular classification. Of course many of the documents dealt with several issues, so cross referencing was an essential part of the process. This was accomplished mainly through note taking and adding lists of documents that were housed in other files to the file in question.

The semi-structured, in-depth interviews.

A total of 44 people were interviewed as part of this research. All of the informants were connected to the shuttle programme and the selection ranged from NASA and contractor engineers to NASA Administrators and contractor managers. Not all those interviewed still work for NASA or the respective contractors. Some have retired and some are now employed in other industries or organizations.

Locating who to interview was the first priority. Before going to the US, contact was made with the American Institute of Aeronautics and Astronautics and the International Association of Machinists and Aerospace Workers to request assistance in the location of informants. The two organizations provided contact names and addresses of people who were, or still are, involved with the shuttle programme. This enabled a foundation to be built, upon which further contacts could be made. While in the US, the NASA History Office, NASA Headquarters, the Kennedy Space Center and the Marshall Space Flight Center, all assisted in suggesting possible people to interview and helped in tracking contact addresses and/or phone numbers. The list of people to interview also "snowballed" from suggestion made by the informants themselves.

The interviews themselves:

The longest interview lasted for 3 hours and the shortest lasted for one half hour. Thus, the interview technique was fluid, adaptable and tailored to the conditions of each particular interview. The primary aim was to allow the informant to talk as much as possible, without interruption. The interview was not, therefore, entered into with a rigid set of questions. The idea was to establish a discussion about the shuttle's history in general and on the informants roles within and recollections of that history in particular. Hence, the only question that was common to all those interviewed was an inquiry into the informants own background; otherwise, in many ways, each interview was unique.

All the interviews were conducted in a friendly atmosphere. No attempt was made to antagonise the informants and all the question were put in a cordial manner. As the interview progressed, notes were taking on what was being said, which shaped the questions then asked. I was always careful, however, not to interrupt the flow and usually waited for the informant to stop talking before I asked a question. This method was chosen because, although I had some background knowledge based on the archive work and secondary source reading, the informants would often raise issues within the conversations that were not obtained from these two sources. However, I did always enter an interview with a rough plan of questions in case the informant was not forthcoming with information.

Shortly after the interview, I would listen to the interview tape and take notes. This aided in two ways: first, it catalogued issues, subjects and topics within the interview; and second, it provided me with knowledge that could be used in another interview. The second transcription, conducted on my return to Edinburgh, was again done in a note taking form. From the notes taking in the US, I constructed an "order of importance" and then worked through this order listening to each tape again. This time a fuller set of notes were taken and specific quotes were drawn out. Tape counter numbers were also added to these notes so that I could locate points of interest easily. The third transcription was conducted as documentary and interview data was reconstructed to tell the history. The tapes were listen to again, using the counter numbers as a guide, and more detailed notes and quotes were drawn from the interviews. Although a full transcription was never completed, the tapes were often listen to repeatedly to maintain an appreciation of their overall content.

Thesis Structure.

History is rarely orderly. Human affairs usually act out a torrent of events and, more often than not, the analyst must impose a sense of order on the chaos. Reconstructing a sociotechnical history of the shuttle was no exception; and the task cannot be described any better than has been so eloquently put by Alex Roland:

> Across the seamless web of history, historians stitch seams. Not to distort the record, or to mislead the reader, but to make sense out of

> chaos. History is a never-ending Bayeux tapestry, interweaving lives and deaths that overlap one another and shape one another. Any story lifted from it must begin and end somewhere.[38]

This historiography begins in 1968, the year NASA announced its intention to build the shuttle. Chapter 2 charts the events that led from this beginning up to 1970; a period that witnessed a sea of change, both for NASA and the wider historical conditions within which it resided. Chapter 3 then follows on up to 1972, when political approval to build the shuttle was finally granted. Thus, the focus of chapters 2 and 3 is *definition*. Together they explore and unveil the sociotechnical web of alliances, conflicts and compromises that shaped both the technology and NASA's goals. Throughout this period the shape of the technology was fluid: continually undergoing definition and redefinition as NASA endeavoured to position the shuttle on the political agenda. The intentions of the two chapters then, are to reveal the underlying forces and dynamics that led to: NASA selecting the shuttle as a major part of its space programme for the 1970s; and caused the programme and, therefore, NASA's position to become unstable; and induced radical effects on the design of the shuttle, its objectives and the objectives of NASA. Although the chapters concentrate on the years between 1968 and 1972, introductions to events, actors and positions are also

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38 Alex Roland, 'Barnstorming in Space: The Rise and Fall of the Romantic Era of Spaceflight, 1957-1986,' Radford Byerly, (ed) ***Space Policy Reconsidered*** (San Francisco, Westview Press, 1989), p 33.

taken into account. This is done to provide some historical background to an emergent network that encircled the shuttle and to capture the changing mood of a nation towards the civilian space programme.

Definition is again the main theme of chapter 4, but this time the focus is on the level of the sub-system. The narrative delves deeper into the technological detail to explore, not just the social forces, but the technical and material shapers of particular shuttle systems. Unpacked are the convergence of sociotechnical relations and interactions that conditioned the forms and functions of major components of the shuttle. Again, histories behind the various sub-systems are traced, and then synthesized with the activities of the period in question, to discover why certain technologies were chosen and others abandoned. The chapter is dense in detail, but that is a necessary part of understanding the dynamics behind the shaping processes.

Chapter 5 turns its attention to *organizational* factors. The fabrication of a technological system of this size and complexity, required, by its very nature, the rigorous organization, management and control of human activity. Social order was an inherent part of the making. The emphasis of this chapter, therefore, is on the construction of the social assemblage that formed around the making of the shuttle. It explores the rise of shuttle's management structure, the development of linkages between the various NASA Centers and their contractors, and their relationships to and impacts on the composition and function of the technologies.

Social scale is climbed twice more in chapters 6 and 8. Wider political, historical and structural conditions (between, 1972 and 1976 for the former, and 1976 and 1981 for the latter) are surveyed to expose their continuing influence on both the technology and NASA. What is explore within these two chapters is how the momentum of large sociotechnical assemblages can change direction, be slowed down, or be halted altogether. Despite the large investments of time, people and resources, retrenchment and cancellation were always possible paths of action. The reasons why the shuttle survived, and how the sociotechnical assemblage adjusted itself against the volatility of its circumstances, are the main issues to be uncovered.

In chapter 7, attention is again turned to the technical detail. The focus this time is on the *fabrication* and *testing* of some of the major components explored in chapter 4. The principal aim of this chapter is to show that closure did not occur at the end of design. Continuous modification, both to the technology and to the social order, is the process that forms the foundation of this chapter. The development of knowledge about the technologies in question; its application to the process of fabrication and predictions about function; and the dialectical relationship between the "working" machines and the engineers attempts to capture material agency, are the key subjects of inquiry.

Whereas the central focus of the previous chapters is on design, development and fabrication, chapter 9 is principally concerned with issues of *operations*. The shuttle's operational environment was very different from that of NASA's old expendable launch vehicles. It entailed a new way of doing things: a change in the organizational culture and in its practice. Thus, reorganization, transformations of practice and philosophy, and the antagonisms between practices of the old and the "demands" of the new, are the matters of study within this chapter.

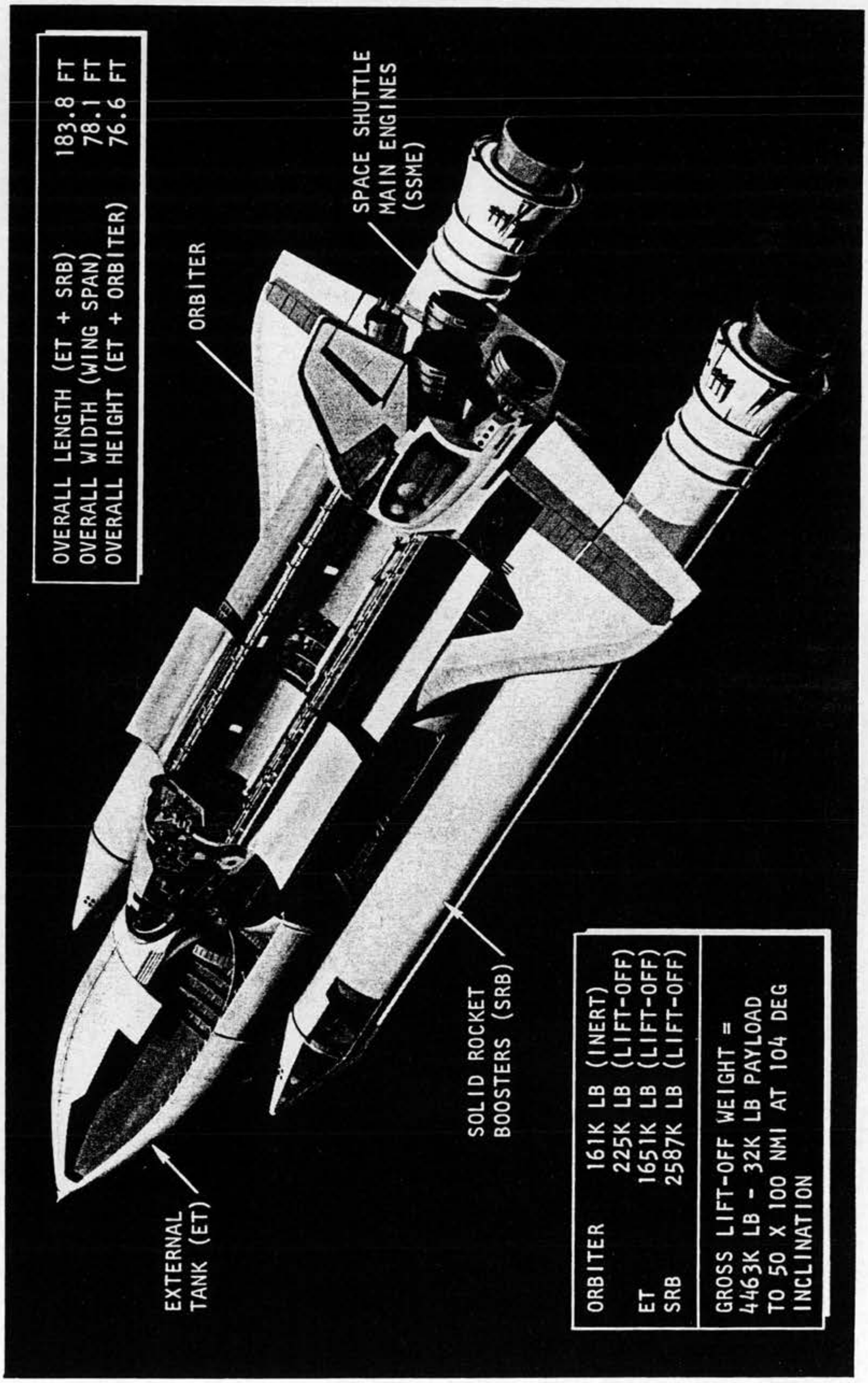
The structure of the thesis is essentially chronological, but, of course, many of the themes that emerge are interwoven with each other in the tangled fabric of the shuttle's history. The purpose of chapter 10, therefore, is to disentangle and tie the threads together: to glean some meaning from the parts in order to make sense of the whole.

Before the narrative begins it is worth highlighting that the term *shuttle* refers to the entire system, which is made up of three major sub-systems: the orbiter, the external tank and the solid rocket boosters (see figure 1:1). Thus, when the term shuttle is used it referring to the entire system, not the orbiter alone.

Figure 1:1.

Source: W.H Morita, (ed) ***Space Shuttle System Summary*** (Rockwell International, Space Systems Group, SSV80-1, May 1980).

Space Shuttle Vehicle



Chapter 2

Definition

> And it ought to be remembered that there is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things. Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new.[1]

NASA, Post-Apollo and the Rise of the Shuttle.

A discreet announcement to an audience of the British Interplanetary Society in early 1968 marked the first public acknowledgement by the NASA Office of Manned Space Flight that it intended to develop a space shuttle.[2] The announcement came as Apollo, NASA's grand mission to land an American on the Moon approached its conclusion. The issue of what to do next had not been fully resolved, but the disclosure did marked a consolidation of thinking within NASA's upper echelons on future programmes, objectives and direction.[3]

NASA had been instructed by the White House to form a post-Apollo plan back in 1964, but NASA's upper echelons

1 Niccolo Machiavelli, ***The Prince,*** trans. W. K. Marriott (London: J.M. dent & Sons Ltd, 1958), p 29.

2 Robert Freitag, interview with author, June 5, 1995; David Baker, 'Evolution of The Space Shuttle: Part 1' ***Spaceflight*** (June 1973), p 202.

3 Le Roy Day, interview with author, 29 June 1995.

were not eager to finalize a follow on programme at that time. They were of the opinion that to do so would make NASA vulnerable and open to criticism, which could divert attention away from the Lunar objective. Vagueness thus became common and disagreement between the NASA Centers flourished. By 1966 the White House no longer wanted to hear about post-Apollo possibilities, nor did it want Congress to hear them. For the first time since the Soviet Union's launch of Sputnik moved space to the centre stage in US politics, a president did not mention space in the State of the Union Message to Congress. The escalation of the Vietnam War in 1965 and the consequential ten per cent tax increase in 1967 to pay for it and President Lyndon B. Johnson's bold social programmes, knocked space off the top of the political agenda. Apollo was secured, but the stance of the White House and Congress took its toll on NASA's future. The Apollo Applications Programme, which would utilize the Saturn/Apollo hardware in near-Earth orbit was approved in early 1967, but the year mark a transition from expansion to retrenchment.[4]

1968 thus witnessed the mobilization of various groups within NASA's space divisions aiming to strengthen their positions, by re-defining the shape of space activity.

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4 Francis Hoban, interview with author, May 15, 1995; Walter McDougall, ***The Heavens and The Earth: A Political History of the Space Age*** (New York: Basic Books, 1985), pp 420-22; Henry Lambright, ***Powering Apollo: James E. Webb of NASA*** (Baltimore: The John Hopkins University Press, 1995); pp 139-141; Henry Lambright, ***Presidential Management of Science and Technology: The Johnson Presidency*** (Austin: University of Texas Press, 1985), pp 142-150; Robert McNamara, with Brian VanDeMark, ***In Retrospect: The Tragedy and Lessons of Vietnam*** (New York, Times Books, Random House, 1995), chapters 7-9.

Those that advocated the development of a space shuttle represented only one of a variety of movements that sought to control the burgeoning realm of space. The NASA Centers devoted to space science saw their hopes ready to expand now that Apollo was nearing completion.[5] But in its 1969 report, *America's Next Decade in Space*, NASA's upper management gave a prominent and permanent position to the human element of the national space programme. Outlined was a quixotic inventory of projects to take the "space age" into the next century, including: three Earth orbiting space stations and one space station in Lunar orbit; a fleet of reusable shuttles that would link the Earth with the three Earth orbiting space stations; a nuclear powered shuttle that would form a link between the Earth space stations and the Moon; a Lunar base equipped with a Lunar Module that would link the ground base with the Lunar orbiting station; and a human expedition to Mars, which would also conduct a fly by of Venus on its journey back to Earth.[6] In the politics of post-Apollo, NASA's higher echelons sought to fortify the organization's position through an expansion of the space enterprise and the creation of a vast new space infrastructure.

Central to the NASA Office of Manned Space Flight was the permanent Earth orbiting space station and a fleet of

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5 Bruce Murray, ***Journey Into Space: The First Thirty Years of Space Exploration*** (New York, London, W.W. Norton & Company, 1990).

6 Francis Hoban, interview with author, May 15, 1995.

reusable shuttles. The concept of a permanent human-inhabited space station had been 'a gleam in the eye of numerous NASA engineers'[7] since the agency was founded. Indeed, the original planning for Apollo incorporated an Earth orbiting rendezvous method, which, NASA planners hoped, would eventually lead to an Earth-orbiting space station by 1967. Nevertheless, pressure to complete Apollo within the time frame set by President John Kennedy in 1961, to land an American on the Moon by the end of the decade, forced NASA to adopt a Lunar orbit rendezvous method. What this effectively meant to some NASA officials was that the agency would have no productive technology with which to establish extensive near Earth orbit operations.[8] For many in NASA, therefore, Apollo was perceived as imparting no logical legacy upon which to build a space infrastructure.[9]

The large Saturn boosters and the Apollo spacecraft were seen as single mission technologies; built to carry people and machines to the Lunar surface (see figure 2:1). Expansion of the space enterprise, in NASA eyes, had to

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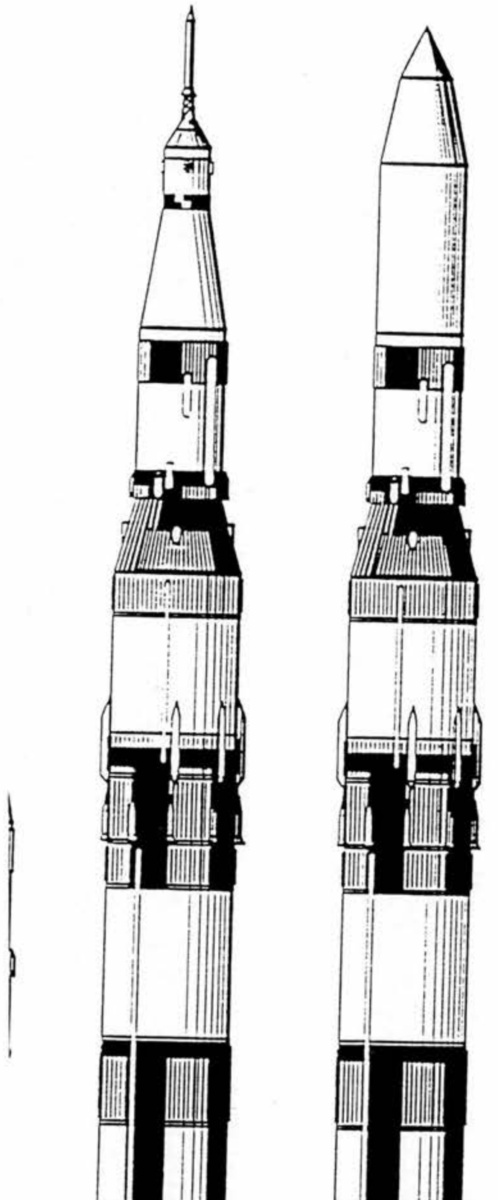
7 Sylvia Fries, '2001 to 1994: Political Environment and the Design of NASA's Space Station System,' Marcel Lafollette, Jeffrey Stine, (ed) ***Technology and Choice: A Technology and Culture Reader*** (Chicago: The University of Chicago Press, 1991), p 234.

8 ***A National Integrated Missile and Space Vehicle Development Program***, Report to the National Advisory Committee for Aeronautics by a special committee on space technology, The Working Group on Vehicular Program, July 18, 1958 (NASA History Office Archives, Washington DC); ***The Long Range Plan of The National Aeronautics and Space Administration***, Office of Program Planning and Evaluation, December 16, 1959 (NASA History Office Archives, Washington DC); James Hansen, ***Enchanted Rendezvous: John C. Houbolt and the Genesis of the Lunar-Orbit Rendezvous Concept*** (Washington DC, NASA History Office, Monographs in Aerospace History Series #4, December 1995).

9 Francis Hoban, interview with author, May 15, 1995.

Figure 2:1.



Source: Joseph Green, Hattret [redacted] *of Major NASA Launches: October 1, 1958 - December 31, 1989* (Florida, KSC Historical Report No.1, June 1992).

rest on operations in near Earth orbit. One shot missions, built and launched from Earth limited future potential. If space was to be conquered then according to NASA, the US needed a steppingstone in near Earth orbit. Rapid growth could only be encouraged by means of a revolution in launch vehicle and spacecraft technology; a revolution in the means would provide a revolution in the ends. A growing contingent, therefore, converged around the idea of developing an entirely new launch vehicle for Earth orbit logistics.[10] Ultimately, this orientation towards leap-frog innovation rather than incremental innovation became dominant because of NASA's penchant for the development of advanced technology. Ideas to move in an incremental fashion and modify both the Saturn or Titan boosters and the Apollo or Gemini spacecraft were quickly silenced.

By the end of 1968 project planning was well under way and by early 1969 the Office of Manned Space Flight had established two task groups, during a reorganization of its management structure; one to take responsibility for the proposed space station and the other to take responsibility for the shuttle. The Space Shuttle Task Group, headed by LeRoy Day, Apollo Test Director, comprised forty people from different Centers and was delegated to evaluate the diverse technical issues and produce a report on the progress and direction of Phase-A shuttle planning. Phase-A

10 William Normyle, 'Large Station May Emerge As Unwritten US Goal,' ***Aviation Week and Space Technology*** (March 10, 1969), pp 103-109.

was the first part of an anticipated four phase shuttle development process. Labelled advanced studies, Phase-A was to be followed by Phase-B, known as project definition and then Phase-C, actual vehicle design and Phase-D, production and operations.[11]

Major sections of the US aerospace industry were involved with NASA's Phase-A shuttle planning studies by early 1969 and by mid-1969 the Space Shuttle Task Group defined six different types of missions that a shuttle should perform:

* Logistical support of a near-earth orbiting space station.
* Placement and retrieval of satellites into near-earth orbit.
* Delivery of other payloads to near-earth orbits.
* Propellant delivery to spacecraft in near-earth orbits.
* Near-earth orbiter satellite servicing and maintenance.
* Short duration manned orbital research missions.[12]

The group also expressed a preference for a fully or near-fully reusable vehicle, but accepted that the challenge of designing an orbital vehicle flexible enough to perform all these diverse missions, whilst also being both economical to develop and operate, demanded a number of trade-offs. As

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11 NASA changed this process as the programme progressed re-terming Phase-A as preliminary analysis, and combining Phases C and D into one. Hans Mark, Arnold Levine, ***The Management of Research Institutions: A Look at Government Laboratories*** (Washington DC, NASA, Scientific and Technical Information Branch, 1984), p 93.

12 Dennis Jenkins, ***Space Shuttle: The History of Developing the National Space Transportation System*** (Wisconsin: Motorbooks International, 1993), p 49.

such the task group listed a number of trade-off studies that they thought should be performed, including:

* Partially or fully reusable systems.
* Piloted flyback booster vs expendable booster.
* Winged vs lifting-body configurations.
* Off-the-shelf engines or new design propulsion systems.
* Vertical vs horizontal launch.
* Low vs high crossrange capability.
* Small vs large payload capability.
* Sequential staging vs parallel-burn.[13]

As 1969 drew to a close, so did the Phase-A studies. A variety of proposals and designs were put forward (see figures 2:2, 2:3 and 2:4), but the Office of Manned Space Flight eventually selected a reusable, two-stage shuttle design as the most promising concept to be examined in Phase-B. The whole shuttle system was designed as two separate vehicles; a booster, about the size of a Boeing 747 that would provide the thrust to lift the system off the Earths surface; and riding piggy-back, an orbiter, about the size of a Boeing 707 that would disengage at between 10 to 20 miles altitude and go on into orbit on its own. Each stage was designed to be piloted, both would be fully reusable and both would fly and land like a conventional aeroplane (see figures 2:5 and 2:6). System life was projected at ten years and each vehicle was to be tailored to a minimum of 100 missions before major

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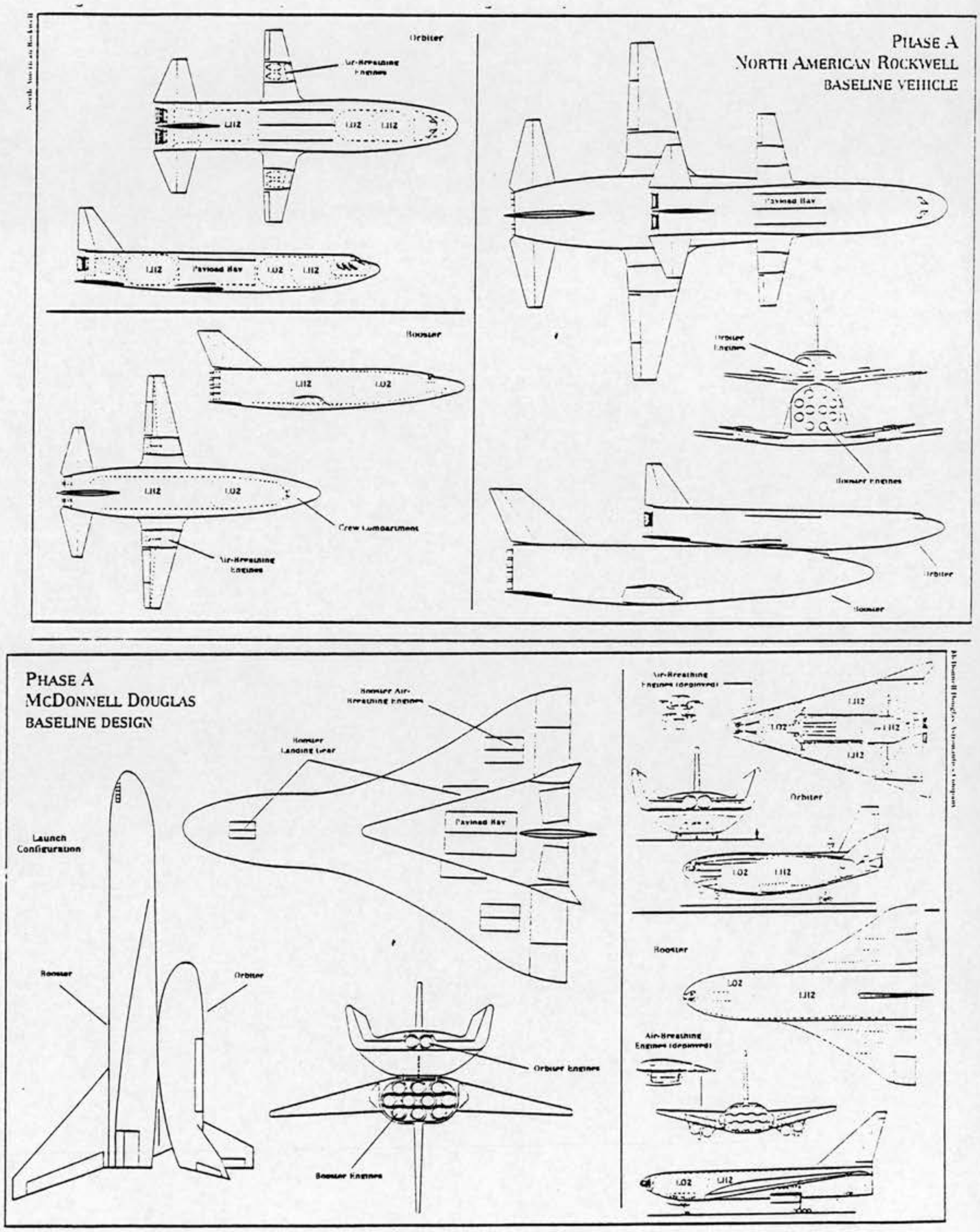
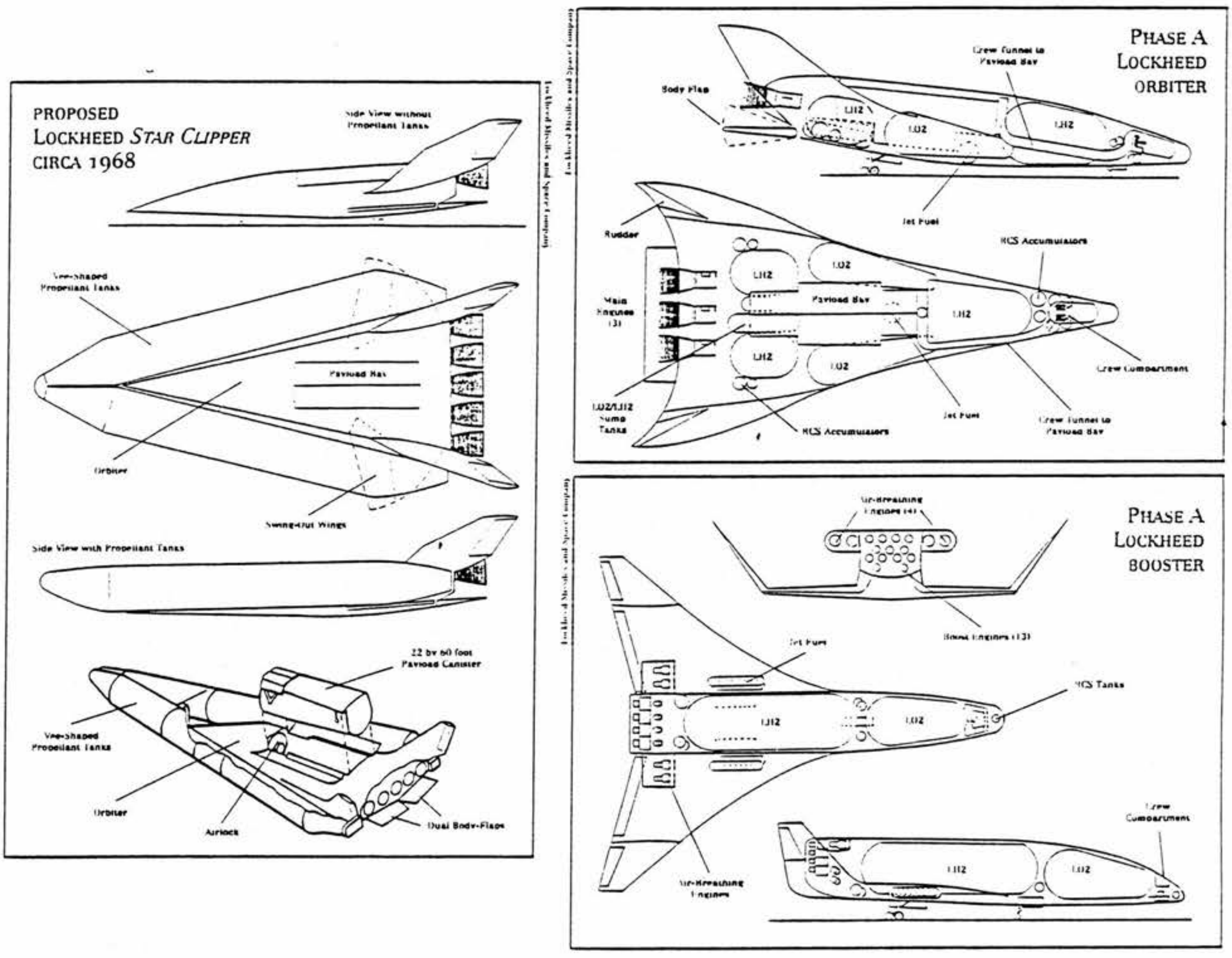
13 *Ibid.*

Figure 2:2.



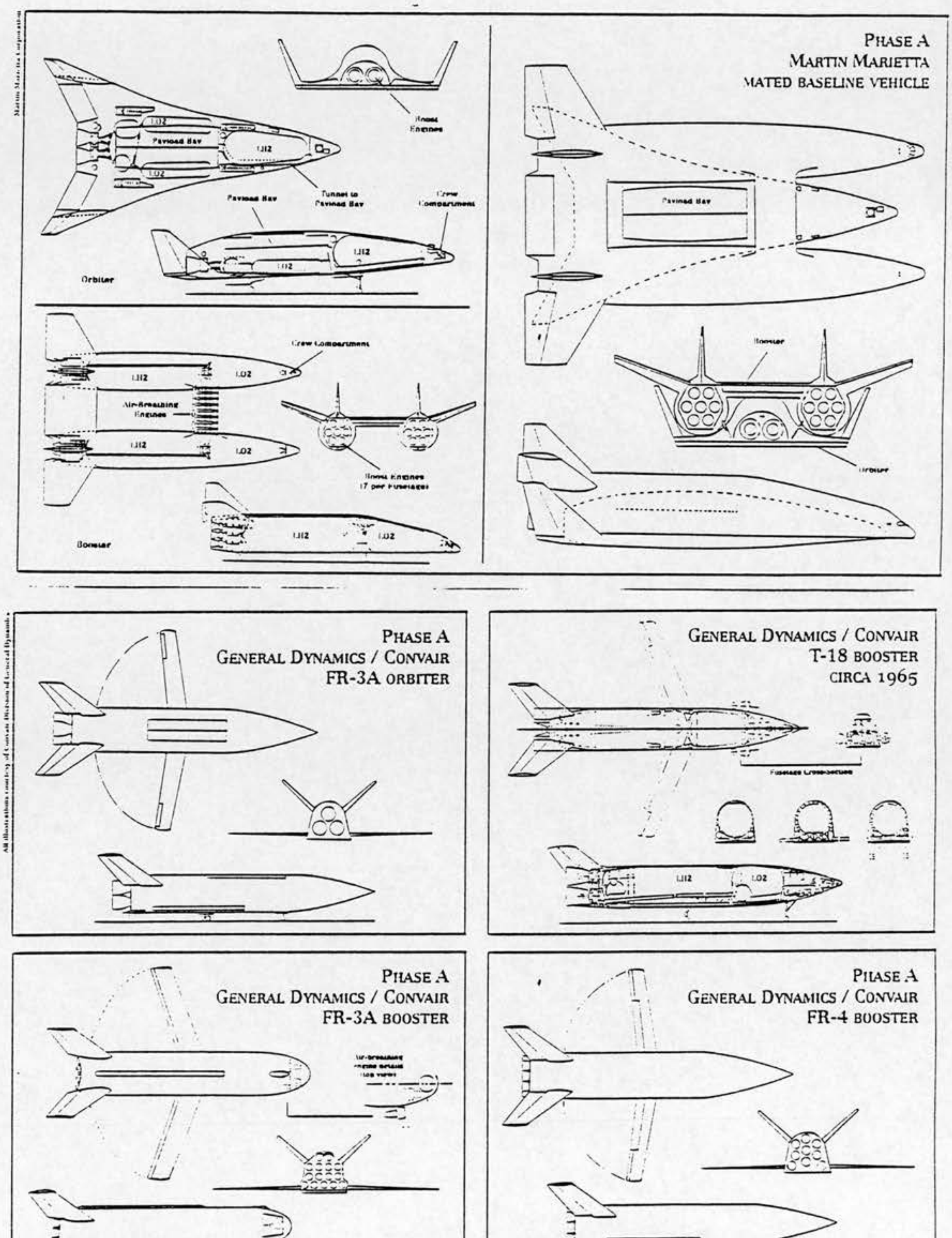
Source: Dennis Jenkins, ***Space Shuttle: The History of Developing the National Space Transportation System*** (Wisconsin, Motorbooks International, 1993).

Figure 2:3.



Source: Dennis Jenkins, ***Space Shuttle: The History of Developing the National Space Transportation System*** (Wisconsin, Motorbooks International, 1993).

Figure 2:4.



Source: Dennis Jenkins, *Space Shuttle: The History of Developing the National Space Transportation System* (Wisconsin, Motorbooks International, 1993).

Figure 2:5.

Source: NASA History Office Archive, Washington DC.

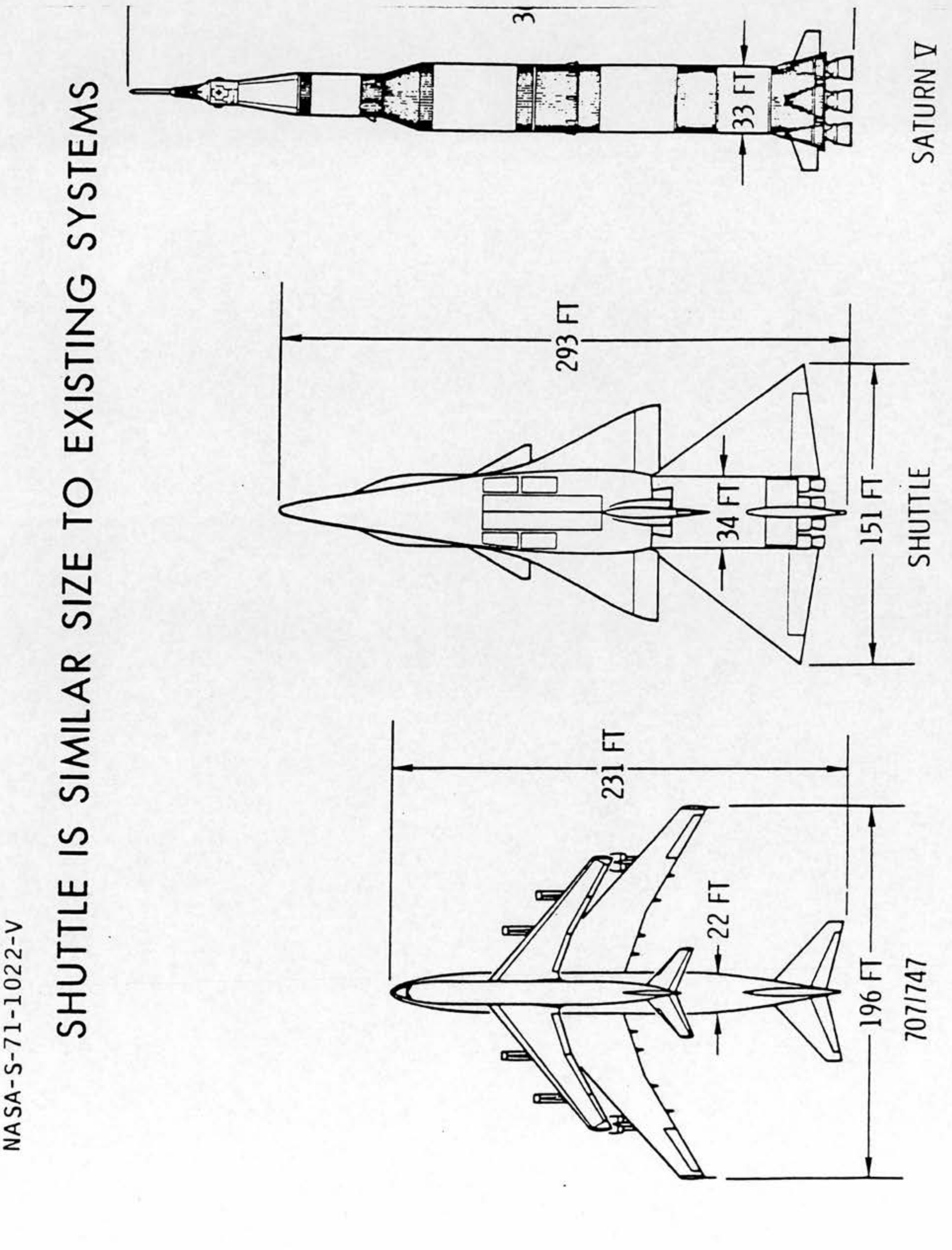
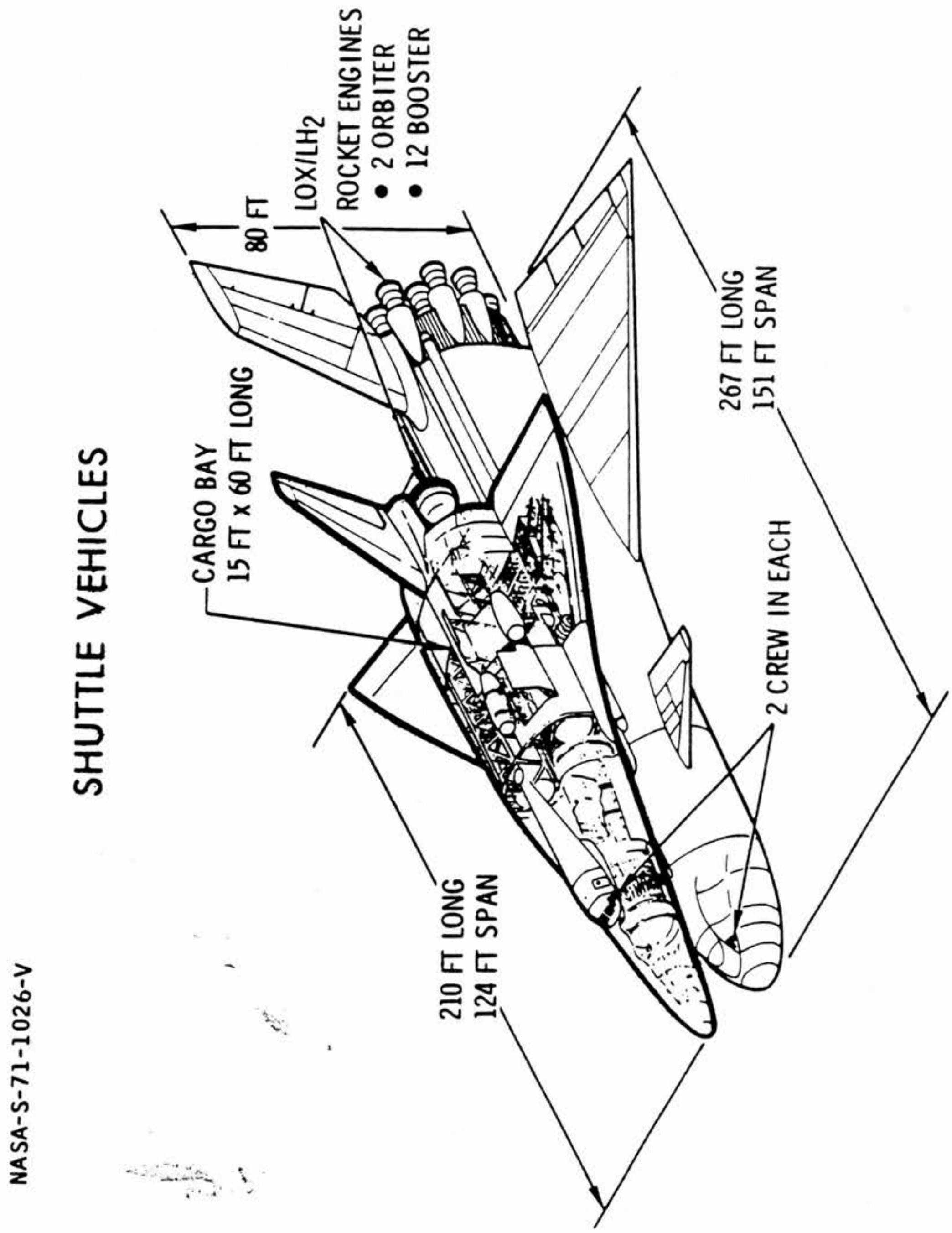


Figure 2:6.

Source: NASA History Office Archive, Washington DC.



refurbishment.[14] It was envisaged that the shuttle would be operational by the second half of 1977 and capable of conducting 75 flights per year by the end of the decade.[15]

The configuration of NASA's proposed space station had also taken shape by mid-1969. Earlier plans to launch a small fully constructed space station had been rejected on the grounds that it would be too conservative in size, scope, and potential accomplishments. Instead, NASA opted for a modular design with the intention of constructing the station in orbit rather than on Earth. This would allow development of a platform that could accommodate up to 100 people by 1980.[16]

The concepts were grandiose in design, potential and cost. In 1969 the estimated cost of development for the space station was put at over $10 billion and $5.2 billion to develop the shuttle. By January 1970 the figure for the space shuttle climbed to just under $10 billion[17] and reached $12 billion before the year concluded.[18] Including the space station, NASA was asking for an investment of well over $20 billion from the American taxpayer.

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14 'Reusable Space Shuttle Effort Gains Momentum,' ***Aviation Week and Space Technology*** (October 27, 1969), pp 22-24.

15 ***Space Shuttle Program Requirements Document: Level 1***, Office of Manned Space Flight, July 1, 1970 (NASA History Office Archives, Washington DC).

16 William Normyle, 'NASA Aims at 100-Man Station,' ***Aviation Week and Space Technology*** (February 24, 1969), pp 16-17; William Normyle, 'Large Station May Emerge As Unwritten US Goal,' ***Aviation Week and Space Technology*** (March 10, 1969), pp 103-109.

17 'Shuttle Group Readies Proposal Requests,' ***Aviation Week and Space Technology*** (January 19, 1970), pp 17-18.

18 Hans Mark, interview with author, September 8, 1995.

Such an outlook was overly optimistic and out of line with the political and economic conditions of the time. 1968 had been a watershed year on many fronts. Incipient contradictions in the consensus politics promoted by both the Kennedy and Johnson Administrations had surfaced by 1967. Riots swept through American cities exposing the fragility of the solutions offered by liberal democracy to the problems of civil rights and social exclusion and destabilizing Johnson's Great Society programme. Opposition to the Vietnam war had also intensified as it escalated.[19] Economic crisis threatened in the spring of 1968 as inflation reached an unprecedented 4.7 per cent and the federal deficit crept towards $25 billion, far more than in any other post war year. Although unemployment remained relatively stable, sections of organized labour, not least in the public services, were showing signs of discontent.[20]

Each of these factors impinged upon NASA's future planning. The most decisive was the collapse of the Democratic hegemony. President Johnson had announced that he would not be seeking renomination for another term; and in an election fought in 1968 over the Vietnam war, support

19 Ronald Segal, ***America's Receding Future: The Collision of Creed and Reality*** (England: Harmondsworth, Penguin Books Ltd, 1968), pp 159-60, 242-244, 252-258, 260-261, 275-278; Although public demonstrations against the war on moral grounds were substantial, there was a larger tide of opinion that opposed the conflict because the cost was to great. Noam Chomsky, introduction to ***American Power and The New Mandarins*** (London, Chatto & Windus Ltd, 1969).

20 Ronald Segal, ***Ibid***; James Reichley, ***Conservatives in an Age of Change: The Nixon and Ford Administrations*** (Washington DC: The Brookings Institution, 1981), p 205, 219; Michael Bradley, 'The Inexorable Rise of the National Dept,' Philip Davis, (ed) ***An American Quarter Century: US Politics from Vietnam to Clinton*** (Manchester and New York: Manchester University Press, 1995), pp 56-57.

for Republican, Richard Nixon grew in strength.[21] Prior to and during his precedency, Johnson's politicking had been crucial to NASA.[22] When the Soviet Union launched Sputnik I in October 1957 he interpreted it as the second Pearl Harbour, an invasion of the skies.[23] The then Republican President, Dwight Eisenhower attempted to play down the significance of the Soviet Union's entry into space,[24] but under political and public pressure during the post-Sputnik paranoia agreed to remodel the National Advisory Committee for Aeronautics to take charge of a new civilian space programme. As Vice President, Johnson convinced the newly elected President Kennedy to recruit NASA in their campaign against a perceived Soviet threat by engaging in the lengthiest battle, en route to the Moon.[25] When Johnson himself became president in 1964, NASA received almost

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21 The first Gallop poll after the Democratic convention showed that Nixon had a substantial lead with 43 per cent of the vote. Richard Nixon, ***The Memoirs of Richard Nixon*** (London: Sidgwick & Jackson Ltd, 1978), p 318.

22 For a detailed analysis of the establishment of NASA see, Enid Schoettle, 'The Establishment of NASA,' Lakoff, (ed) ***Knowledge and Power*** (New York: Free Press, Collier-Macmillian Ltd, 1966). For detailed histories of the Apollo space programme see, Mary Holman, ***The Political Economy of the Space Program*** (Pacific Books, 1974); John Logsdon, ***The Decision To Go The Moon: Project Apollo and The National Interest*** (Cambridge MA: MIT Press, 1970); Walter McDougall, ***The Heavens and The Earth***; Dale Carter, ***The Final Frontier:The Rise and Fall of the American Rocket State*** (London, New York: Verso, 1988); Henry Lambright, ***Powering Apollo***.

23 Dale Carter, ***The Final Frontier*** p 127; John Logsdon, ***The Decision To Go To The Moon*** pp 21-22; Enid Schoettle, 'The Establishment of NASA,' pp 185-186, 220-229; Walter McDougall, ***The Heavens and The Earth*** pp 141, 148-149; H. Young, B. Silcock, P. Dunn, ***Journey to Tranquillity: The Long Competitive Struggle To Reach The Moon*** (New York: Doubleday & Co Inc, 1970), p 53.

24 As Walter McDougall has demonstrated, the Eisenhower Administration had been anything but complacent since the Technologies Capabilities Panel Report in 1955, accelerating research and development of both missiles and satellite technology. None of this work could be made public for security reasons. Such concerns with space strategy over propaganda left Eisenhower open to attack, but as McDougall emphasis, loss of public face was less important than loss of potential secret satellite intelligence. In practice ***Sputnik*** proved strategically beneficial to the US since it precluded potential Soviet challenges to the legality of American satellite overflight. Walter McDougall, ***The Heavens and the Earth*** pp 111, 117-124, 128, 221, 224.

25 Dale Carter, ***The Final Frontier*** p 158.

unqualified support from his administration despite political opposition and programmatic friction between Apollo, the Vietnam War, and the Great Society programme. A victorious outcome for the US in the space race was regarded as so important that NASA was in a position to continue with its project no matter what the cost. Even the deaths of three astronauts in the Apollo fire of 1967 did not deter NASA or the government from persisting with its main objective; to beat the Soviets to the Moon.[26] Johnson's departure from office thus had an important bearing on the political support NASA would receive for its post-Apollo planning. Its immediate consequence however, was to influence the departure of another significant individual, James Webb.

Appointed as NASA Administrator in 1961, Webb has been described as the power behind Apollo.[27] His management skills and political sophistication were well recognized within NASA.[28] Webb's leadership unquestionably led to the location of the Manned Spacecraft Center in Texas and the building of the southern crescent;[29] a political manoeuvre which assured NASA powerful congressional support. By

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26 For a detailed analysis of the Apollo Fire and its aftermath see Henry Lambright, ***Powering Apollo*** pp 142-188.

27 ***Ibid.***

28 Francis Hoban, interview with author, May 15, 1995.

29 Walter McDougall, ***The Heavens and the Earth*** pp 373-374; Henry Lambright, ***Powering Apollo*** pp 106-107. The Manned Spacecraft Center was renamed the Lyndon B. Johnson Space Center on February 17, 1973. Further references will cite the Manned Spacecraft Center as the Johnson Space Center notwithstanding the time period.

locating NASA facilities right across the south at a time when these areas were trying to get out from an agricultural based economy, Webb managed to make powerful members of the Congress 'stakeholders in Apollo'.[30] After Johnson's announcement of departure, Webb became concerned that the agency's leadership would become a political issue. If he was still NASA Administrator after the election political conflict would be inevitable. Vice President Hubert Humphery, the Democratic favourite, and Webb had had tensions and if Nixon succeeded then it was likely that Webb would be removed. Webb felt that his removal would also cut deeper into NASA's leadership, with Nixon excising those that he regarded to be loyal to Webb or Johnson. After a meeting with Johnson on September 17, 1968, Webb announced his retirement and Thomas Paine, NASA's Deputy Administrator, took up the reins.[31] In November 1968, Nixon won the presidential election and the new administration took office in January 1969.

Over 1.5 billion people around the globe witnessed the planting of Old Glory at Tranquillity Base,[32] assuring Neil Armstrong's place in history as the first man to walk on

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30 Francis Hoban, interview with author, May 15, 1995.

31 Henry Lambright, ***Powering Apollo*** pp 200-205.

32 Mary Holman, ***The Political Economy of The Space Program*** p 5.

the Moon on July 20 1969.[33] In the public's eyes, NASA had reached the zenith of the "space age".

> At jet-set parties in Paris, grand tribal fires of Southern Zambia, in the courtyards of Buddhist temples in Bangkok, on street corners in Colombo, Ceylon, and in snug Dublin pubs millions huddled close to TV sets or radios as the Apollo voyage was described in dozens of languages. For days newspapers, radios, and television stations throughout the world have featured the historic space journey, often giving little attention to domestic issues. It seemed as if there were no part of earth unaware that two men had set foot where no man had gone before.[34]

Over ten years of planning, research, development, and production accomplished what has been called the 'greatest engineering feat of all time.'[35] The Apollo euphoria was, nonetheless, short lived. Rather than a mechanisms for uniting a nation, Apollo reflected its divisions. Not missing the potential of good publicity, the newly elected President Richard Nixon, had declared July 20, 1969 a 'National Day of Participation'. But the events of the day were not universally shared. Although exemplified as the embodiment of the "frontier spirit" of America, Apollo remained at odds with everyday life.

> In St. Louis hundreds of AT&T employees went on strike when management declined to follow the Presidents lead; and in California most aerospace

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33 Astronauts Armstrong and Aldrin, landed the Lunar Module to the Moons surface, leaving Collins in the Command Module. Armstrong became the first human to set foot on the Moon at 9:56 pm (EDT). They remained on the surface for a period of 21 hours, returning to a splash down in the Pacific Ocean on July 24. Linda Neuman Ezell, ***NASA Historical Data Book Volume III: Programs and Projects 1969-1978*** (Washington DC: The NASA History Series, Scientific and Technical Information Division, 1988), p 74.

34 ***The New York Times*** (July 21, 1969).

35 Francis Hoban, ***Where Do You Go After You've Been To The Moon: A Case Study of NASA's Pioneering Effort at Cost Control with Prescriptions for Today*** (Virginia: Draft Manuscript, George Mason University, 1995), p 1.

> companies likewise refused to pay their workers to sit at home watching the fruits of their labour. ... Even as Apollo XI made its way to the moon, Wall Street analysts were forecasting an unpromising future for aerospace stocks in the context of declining NASA expenditure, conditions which only underlined the need for the workers to stick at their tasks. And even as 8,000 Western Electric Employees voted with their seats and stayed home anyway, the Houston garbage workers ... elected to work through the day: quite simply, they needed the cash.[36]

Discontent quickly spilled over into the space programme. Student groups from Boston and New York disrupted meetings of the American Association for the Advancement of Science, and formed picket lines at a NASA exhibition of Lunar rock brought back from Apollo XI.[37] Hans Mark, then director of NASA's Ames Center, recalled a formal dinner, hosted by the President, to celebrate the return of the Apollo XI astronauts. He described the atmosphere inside the Century Plaza Hotel, Los Angeles, as both 'festive and patriotic'.[38] Outside a large demonstration had amassed. Its message, a brusque reply to the advocation by Vice President Spiro Agnew that Americas next venture in space should be a 'manned flight to Mars by the end of this century.'[39]

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36 Dale Carter, ***The Final Frontier.*** p 225.

37 'Space Effort Attacked,' ***Aviation Week and Space Technology*** (January 5, 1970) p 16.

38 Hans Mark, ***The Space Station: A Personal Journey*** (Durham: Duke University Press, 1987) p 37; Hans Mark, interview with author, September 8, 1995.

39 Spiro Agnew, quoted in Scott Pace, ***Engineering Design and Political Choice: The Space Shuttle 1969-1972*** (MIT, Massachsetts: Unpublished MS Dissertation, 1982), p 20.

> A major feature of the demonstration was a huge sign with the legend "Fuck Mars" printed on it in large letters that the demonstrators had somehow been able to hang along the upper floors of one of the office buildings across the street from the Century Plaza. The same message was clearly repeated on signs that some of the demonstrators carried.[40]

Political activists were not however, alone. The very success of the Moon landing led to a general public disinterest in space.

> The public had been exposed to at least a decade of intensive media attention to "getting to the moon". It had been a topic of curious speculation for centuries. Once the first landing occurred that interest was forever terminated. ... In this sense public support for the Apollo program had been designed to self-destruct on the initial achievement of the program's major objective.[41]

Leaders within the agency feared that NASA's decline would be sharp without continued public support. Television had become an important medium for NASA, beaming their achievements back to a captivated audience on Earth. Soon after Armstrong's historic footsteps NASA's TV ratings dropped rapidly. George Low, NASA Deputy Administrator, put together a group of very senior NASA officials to address this problem. Nicknamed the Think Group, discussions centred on efforts to create a TV extravaganza during Apollo's next visits to the Moon.[42] All of their endeavours

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40 Hans Mark, ***The Space Station*** p 37

41 Francis Hoban, ***Where Do You Go After You've Been To The Moon*** p 3.

42 The "Think Group" consisted of George Low; Wernher von Braun, Chief of NASA Planning Robert Jastrow, Director of the Goddard Institute for Space Studies; Homer Newell, Associate Administrator; Edward Cortright, Langley Research Center Director; Richard McCurdy, Associate Administrator for Organization and Management; and others as invited. The group spent a great deal of time debating the value and appeal of watching an astronaut pushing a boulder into Hadley Rille. The slow motion fall of a huge rock into a deep canyon at one-sixth gravity

failed and public curiosity continued to drop, and was only briefly rekindled during the abortive flight of Apollo XIII.

Political support for Apollo was also decidedly weak. The Lunar landing signalled a turning point. With the space race won, many in the political arena believed that the programme could now be terminated.[43] Apollo was to include nine further visits to the Moon after the initial landing, but pressure on NASA's fiscal year (FY) 1971 budget forced the agency to phase out production of the Saturn rocket and cancel the final two Lunar landings.[44] NASA astronauts visited the Moon on December 11, 1972 for the last time, and have not returned since.

The question of what to do after Apollo thus entered the political arena again in early 1969. NASA's Apollo Applications programme had been severely downsized in the politics of 1967 and 1968 and the agency had no mission objectives beyond the mid-1970s. The newly formed Nixon Administration did not place civilian space activity very high on its agenda and instead of making any immediate announcement it decided to establish a Space Task Group to examine the issue. Chaired by Vice President Spiro Agnew,

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would prove incredible, but the scenario was dropped when the danger was pointed out of the astronaut falling in behind the boulder. Several attempts at viewer stimulation were made, including the feather and hammer drop, racing the Lunar Rover and playing Golf. These stunts tended to reinforce public scepticism rather than capture their attention. ***Ibid.*** pp 2-6; Francis Hoban, interview with the author, May 15, 1995.

43 M. Smith, 'The First Quarter-Century of Space Flight,' M. Schwarz, P. Stares, Ed 'Space - Past, Present, and Future' ***Futures,*** 14 (October 1982), p 356.

44 Letter to Senator William Proxmire from George Low, September 28, 1970 (NASA History Office Archives, Washington DC).

the Space Task Group consisted of a variety of actors, including the new NASA Administrator, Thomas Paine[45] and was charged with providing a 'definitive recommendation on the direction the US space program should take in the post-Apollo period'.[46] In addition to the Space Task Group, several other planning activities were also under-way. The President's Science Advisory Committee had established the Branscomb committee, headed by Lewis Branscomb, then director of the National Bureau of Standards; and within NASA, George Mueller, Associate Administrator for Manned Space Flight, had expanded the Office of Manned Space Flight's management committee.

The Space Task Group reported at the end of 1969 and provided a selection of spending options that ranged between a *maximum pace*, where the limits were set by technology, not available funding; and a *low level pace*, which did not include any human missions for the 1970s, (see table 2:1). Paine and Agnew, both endorsed a human expedition to Mars as the next logical step in space exploration. The Office of Manned Space Flight, however, were still pushing hard for the development of the space shuttle and the space station. Whereas the President's

45 STG included representatives from NASA, Defence Secretary Malvin Laird, Secretary of State William Rogers, Science Advisor Lee DuBridge and representatives from the State Department, the Atomic Energy Commission, and the Bureau of the Budget. Input was also received from members of Congress, the National Academy of Sciences, the American Institute of Aeronautics and Astronautics, private citizens and industry. Normyle W. 'Broad New Space Program Urged,' ***Aviation Week and Space Technology*** (August 11, 1969) pp 22-23.

46 ***The Post-Apollo Space Program: Directions For The Future***, Space Task Group report to the President, September 1969 (NASA History Office Archives, Washington DC), p 19.

Table 2:1.

Comparative Programme Accomplishments.

Milestones	Maximum Pace	Programme I	Programmes II, III	Low Level
Manned Space Systems.				
Space Station (Earth Orbit)	1975	1976	1977	-
50 Man Space Station	1980	1980	1984	-
100 Man Space Station	1985	1985	1989	-
Lunar Orbiting Station	1976	1978	1981	-
Lunar Surface Base	1978	1980	1983	-
Mars Expedition	1981	1983	II-1986	-
			III-Open	-
Space Transportation Systems.				
Earth to Orbit	1975	1976	1977	-
Nuclear Orbit Stage	1978	1978	1981	-
Space Tug	1976	1978	1981	-
Scientific.				
Orbiting Observatory	1979	1979	1980	-
Mars Mapping	1977	1977	1981	1977
Venus Probes	1976	1976	Mid-1980s	1976
Outer Planet "Tours"	1977-79	1977-79	1977-79	1977-79
Astroid Belt Survey	1975	1975	1981	1975
Applications.				
Earth Resource Systems	1975	1975	1976	1975
Direct Broadcasts	1978	1978	mid-1980s	1978
Navigation/Traffic Control	1974	1974	1976	1974

Source: Adapted from Table 1, ***The Space Program in the Post-Apollo Period*** p 20.

Science Advisory Committee's followed its earlier position, and recommended that NASA should concentrate its efforts on only developing a reusable transportation system for the 1970s.[47] Moreover, the President's Science Advisory Committee suggested that planetary exploration should be conducted by automated equipment and NASA should adopt a slow pace development of a space station; examining its viability during the 1970s and progressing to full development in the 1980s.

It was clear that a schism was beginning to develop between the ideas that were being generated by the Office of Manned Space Flight and the ideas that were being considered by the other actors. The Office of Manned Space Flight placed the highest priority on the creation of new technologies to operate in space. What would actually be done with these technologies was secondary in importance. In contrast, the Space Task Group, the President's Science Advisory Committee and other areas of NASA concentrated on mission objectives. Technology was seen as something that would have to be created in order to execute the missions that were being proposed.[48] Notwithstanding this rift, the Office of Manned Space Flight was successful in translating its interests into the interests of the other groups. By

47 The PSAC had released a report in early 1967 entitled ***The Space Program in the Post-Apollo Period***, which recommended that studies should concentrate on more economic systems for the delivery of payloads to orbit. The impact of the report was minimal as it had come at a time when the Johnson Administration was preoccupied with the escalating Vietnam war. The United States poured more money into the war in 1967 alone than it spent on the entire Apollo programme.

48 Hans Mark, ***The Space Station*** p 33.

advancing the idea that the shuttle and the space station represented steppingstones in space, the Office of Manned Space Flight managed to persuade each of the groups to include at least one or the other in their proposals. This strategy was particularly effective with the Space Task Group who incorporated the shuttle in three out of four of its options.[49]

In the immediate politics of post-Apollo, NASA's higher echelons sought allegiance with the White House through the chair of the Space Task Group, Vice President Spiro Agnew, in the expectation that his approval would result in a new mandate. It was a strategy that initially appeared to work. Agnew endorsed NASA's grand plans and the agency had partial success in influencing the direction of the other groups involved in the post-Apollo planning. NASA soon found however, that it had few friends in the White House and was entering a new world of post-Apollo with no real identity.[50]

Forces of Resistance.

Richard Nixon carefully monitored political reaction to the post-Apollo planning reports before delivering his space policy message in March 1970. The message was considerably less ambitious than even the third option offered by the

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49 Jerry Grey, ***Enterprise*** (New York: William Morrow and Co Inc, 1979), p 55.

50 Francis Hoban, interview with the author, May 15, 1995.

Space Task Group. It did not include any commitment to a space station, a shuttle, or an expedition to Mars. Instead Nixon expressed the need for a *balanced space programme* which would combine all the elements of exploration, accumulation of scientific knowledge, and practical applications. Studies into the development of a space station and a shuttle were indicated, but no new projects were detailed. Nixon's submission of NASA's Fiscal Year (FY) 1971 budget to the Congress remained well below the $4 billion minimum needed if NASA were to begin its programme in that fiscal year.[51]

NASA's budget had been slowly reduced from its peak of 0.9 per cent of GNP in FY 1966, to 0.47 per cent of GNP in FY 1969. The primary objective pursued by NASA Administrator, Thomas Paine, was to reverse this trend and push for an investment commitment of 1 per cent of GNP.[52] Agnew gave his patronage to a venture on the scale of Apollo, but the shapers of space policy were vastly out of step with the shapers of macro-economic policy. Fiscal and monetary constraint were the primary tools advocated by the Council of Economic Advisors, to stave off the threat of economic crisis, perceived because of the growing federal deficit, a slow down in economic growth, high inflation and signs of rising unemployment. The dictation of economic

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51 Jerry Grey, ***Enterprise*** p 55.

52 William Normyle, 'Broad New Space Program Urged,' ***Aviation Week and Space Technology*** (August 11, 1969), p 23.

policy was thus a maintenance of a federal budget in which expenditures would be matched by revenues.[53] Policy implementation was under the control of the newly formed Office of Management and Budget[54] and they were showing a growing concern over NASA's lack of justifications for its expensive programmes. The Office of Management and Budget's impression of NASA was of an organization that pushed technological innovation for innovation's sake. Officials within the Office of Management and Budget were thus determined not to get snowed under by NASA's requests for advanced technological challenges.[55]

Sceptical of NASA's development cost estimates, the Office of Management and Budget directed the agency to conduct a cost-benefit analysis of its proposed shuttle design. At the end of this study, NASA projected development costs of between $6.4 to $9.6 billion for its fully-reusable, two-stage shuttle system.[56] Unconvinced, the Office of Management and Budget made an extraordinary manoeuvre and demanded that NASA contract an outside evaluation of shuttle development costs. NASA's upper

53 James Reichley, ***Conservatives in an Age of Change*** pp 205-211; Michael Bradley 'The Inexorable Rise of the National Dept,' Philip Davis, (ed) ***An American Quarter Century: US Politics from Vietnam to Clinton*** (Manchester and New York, Manchester University Press, 1995), pp 56-57; John Kenneth Galbraith, ***The New Industrial State*** (England: Harmondsworth, Penguin Books, 1977), pp 96-97, 243, 250-262.

54 The Office of Management and Budget replaced the less powerful Bureau of the Budget early in 1970.

55 Henry Lambright, ***Presidential Management of Science and Technology*** pp 141-151; Claude Barfield, 'Intense Debate, Cost Cutting Precedes White House Decision to Back Shuttle,' reprinted in ***Congressional Record - Senate*** (October 3, 1972).

56 Claude Barfield, ***Ibid.***; Scott Pace, ***Engineering Design and Political Choice*** pp 27-28.

management were reluctant to conduct such a study, fearing that it would raise the whole issue of what constituted a *good* space programme. Nevertheless, given the political climate, NASA bowed to White House pressure and contracted Aerospace Corporation and Lockheed Corporation to assess the impact of the shuttle on reducing payload and launch costs; and Mathematica Incorporated, to provide an overall economic analysis.[57]

The Office of Management and Budget were not the only White House agency seeking control over NASA's activities. The Office of Science and Technology and the President's Science Advisory Committee also demonstrated apprehension over both the costs and the technological risks associated with the agency's proposals. In the summer of 1971, the Presidents Science Advisory Committee established a high level scientific panel to examine NASA's post-Apollo plans. Chaired by Alexandria Flax, President of the Institute for Defense Analysis, the Flax panel worked closely with the Office of Science and Technology and the Office of Management and Budget to curtail NASA's ambitious plans. Critical of NASA's programme cost estimates, the Flax panel concluded that cost overruns could be in the region of 30 to 50 per cent. Armed with an open mandate, the Flax panel also focused attention on technological matters. In an

57 John Logsdon, 'The Decision to Develop the Space Shuttle,' ***Space Policy*** (May, 1986), pp 103-119; John Logsdon, 'The Space Shuttle Program: A policy Failure?' ***Science*** (May 30, 1986), pp 1099-1105.

effort to reduce research and development costs, but still retain a national space programme, the panel expended a lot of energy on proposing alternatives to NASA's baseline shuttle design. While making no single recommendation, the panel did outline three alternative options: (i) defer the decision on new technology until a later data; (ii) develop a new expendable ballistic launch vehicle; or (iii) develop a small partially reusable launch vehicle.[58]

The major difference between NASA and the White House on the type of space transportation system required revolved around a trade-off between operational costs and development costs. The shuttle designs that had emerged from the Phase-B studies reflected NASA's orientation towards supporting heavy logistics. The underlying assumption was that the shuttle's primary function would be to construct a space station. Emphasis was thus on technical viability rather than design economics. Development costs were, therefore, secondary to a system designed around reducing operational costs.[59] The White House however, wanted to disembark from a heavy funding curve. Consequently, many of NASA's debates in Washington were related to the annual funding of its proposed programmes; as Space Shuttle Manager, Robert Thompson recalled:

58 Claude Barfield, 'Intense Debate, Cost Cutting Precedes White House Decision to Back Shuttle.'

59 David Baker, 'Evolution of the Space Shuttle,' ***Spaceflight*** p 230.

> A lot of our debates in Washington had to do with what the annual funding in support of the program would be. And I know lots of times up there the meetings would kind of come to the bottom and say, we don't care what you build, but we don't want the annual funding to get over $1 billion a year.[60]

In the fragile politics of post-Apollo, NASA discovered that many members in both houses of Congress had also developed a negative response to the costly and seemingly intangible proposals coming from the agency. Opponents in the Congress to funding large technological programmes had steadily mushroomed as social, political and economic conditions declined. Agnew's endorsement of a mission to Mars was considered too ambitious and found little support.

> I do not at this time wish to commit ourselves to a specific time period for setting sail to Mars.[61]

> I just for the life of me can't see voting for monies to find out whether or not there is some microbe on Mars, when in fact I know there are rats in the Harlem apartments.[62]

Within the House of Representatives two main issues dominated the space policy debate during 1970 and 1971; whether to support NASA's proposals for human space flight; and whether space programmes should receive such a large slice of the national budget. Some members of the

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60 Robert Thompson, interview with the author, September 7, 1995.

61 Chairman of the Committee on Science and Technology, George Miller (Democrat, California), quoted in Ken Hechler, ***Towards The Endless Frontier: History of the Committee on Science and Technology, 1959-79*** (Washington DC: US Government Printing Office, 1980), p 269.

62 Edward Koch (Democrat, New York), quoted in ***Ibid.*** p 274.

subcommittee on Space Science and Applications and the subcommittee on Advanced Research and Technology positioned themselves against the quixotic visions of a post-Apollo age. In an address to the American Institute of Aeronautics and Astronautics, Space Science and Applications subcommittee chairman, Joseph Karth (Democrat, Minnesota), condemned the Space Task Group's report as 'totally unrealistic' and went on to say:

> Based on my experience ... NASA's projected cost estimates are asinine. ... NASA must consider the Members of the Congress a bunch of stupid idiots. Worse yet, they may believe their own estimates - and then we really are in bad shape.[63]

In the House, Karth focused his attack on the space shuttle declaring:

> Here we are going into contracts on the Shuttle which for all practical purposes is a new program, not even a year old, and we haven't done the basic research necessary ... to determine just how this Shuttle vehicle ought to be built. ... I predict on the record right here that program will cost at least three times what NASA today is saying it is going to cost.[64]

It was the decision by NASA to delay several space science and applications projects so that room could be made for the space station and the shuttle as budget items that led the Space Science and Applications subcommittee to campaign against both programmes.[65] The group however, were up

63 *Ibid.* p 274.

64 *Ibid.* p 273.

65 Jerry Grey, ***Enterprise*** pp 65-66; John Logsdon, The Decision to Develop the Space Shuttle,' p 106.

against powerful support from both the Manned Space Flight subcommittee and some influential members on the Committee on Science and Technology. In 1970, Chairman of the Committee on Science and Technology, George Miller (Democrat, California), announced his intention to hold all NASA authorization hearings within the full committee. This effectively centralized power in the full committee at the expense of the subcommittees; a sharp contrast with traditional practice where the subcommittees had ample opportunity to probe deeply into NASA's projected programmes in detailed public hearings.[66]

When the debates unfolded on the House floor it was evident where the battle line had been drawn. The Manned Space Flight subcommittee jostled to increase NASA's budget for human space flight and the Space Science and Applications subcommittee, sought to fix the human space flight budgets under the Office of Management and Budget's recommendations. In 1970, Chairman of the Manned Space Flight subcommittee, Olin Teague (Democrat, Texas), angered by the proposed cuts, told the House:

> I think that our subcommittee ... have got a good feeling for this thing, and I don't think we have to rubber stamp something the [Office of Management and Budget] does. ... What should we do, just sit back on our cans and let the [Office of Management and Budget] dictate every damn thing we do?[67]

66 Ken Hechler, ***Towards the Endless Frontier*** p 271.

67 ***Ibid.*** p 276.

A continuing rise in unemployment during 1970 spurred many in the House to increase public spending; and John Wydler (Republican, New York), expressed a common sentiment in 1971 when he told the House during a shuttle authorization debate:

> I have been going along with these cuts year to year. I really feel we have reached a point where we should stand up and say "enough." ... I think we had better start redirecting the public's attention to the fact they ... [are spending public money] ... to hire American people, to do American productive work.[68]

Nevertheless, there were others who contended that at a time when budget constraints were most severe, it did not make sense to spend vast sums on human space flight. Charles Mosher (Republican, Ohio), told the House in 1970:

> We must put relatively greater emphasis on those aspects of the space program [where] the practical returns are the greatest ... to the human beings right here on earth.[69]

1970 had witnessed the most significant debate in the House. Opposition to the shuttle and the space station was at its height and as the debate progressed it became apparent that the position of the Republicans represented a crucial swing element. When the roll was called to eliminate both the shuttle and the space station it was clear that the vote was going to be close. As the final count came in both George Miller, supporter of the programmes and Joseph Karth, its most vocal opponent,

68 *Ibid.* p 285.

69 *Ibid.* p 277.

announced their total votes as 53 each, which meant that on a tie vote the amendment to eliminate funding for the shuttle and the space station just failed. Louis Frey (Republican, Florida), recalled the event:

> I'd lobbied pretty hard with the freshmen, and after the first rush of people went through, one of the freshmen from Maryland came rushing in from a meeting and went through the line on our side. He was followed by another Maryland Congressman. The gavel came down, it was announced to be a tie vote, and so the Shuttle stayed in. The second Maryland Congressman said ... I went through the wrong way! As I look at the Shuttle now, I often wonder what would have happened if he'd walked through the right way.[70]

By 1971, the opposition in the House to funding human space flight had dramatically declined. The subcommittee on Space Science and Applications failed to bolster support and Olin Teague's Manned Space Flight subcommittee successfully increased the shuttle budget from the $100 million advocated by the Office of Management and Budget, to $125 million.[71]

Yet, as support for the shuttle rose in the House of Representatives, opposition mounted in the Senate. Led by Walter Mondale (Democrat, Minnesota) and William Proxmire (Democrat, Wisconsin), the Senate debate revolved around the impact that NASA's space station and shuttle development programme could have on the scientific exploration of space. With a government investment that

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70 *Ibid.* p 278.

71 *Ibid.* pp 284-286.

could eventually cost the taxpayer $100 billion, argued Mondale and Proxmire, "space science" programmes would be severely curtailed. Many space scientists, both in academia and NASA, saw their hopes for space science programmes ready to expand once Apollo was nearing completion. The rise of another large, human centred programme sent a wave of consternation through the space science community. Once again their goals looked in danger of being submerged. Riding on the support from disgruntled space scientists, Mondale sponsored an amendment to eliminate both the space station and the shuttle from NASA's FY 1971 budget.[72]

> Even James Van Allen, prestigious discoverer of the vast radiation belts that bear his name, enriched Mondale's arsenal with a letter stating unequivocally that scientific purposes could be served by an unmanned program at least as well as - and considerably cheaper than - manned flights.[73]

Support for the human space programme in the past had come from Senator Clinton Anderson (Democrat, New Mexico) chair of The Aeronautical and Space Sciences Committee. Plagued by ill health, Anderson had taken little interest in the debate or in the essential pre-vote politicking. Responsibility for marshalling support for the space station/shuttle, therefore, fell on the shoulders of the committee staff. Staff member Glen Wilson, 'an old hand in the behind the scenes manoeuvring of the Senate', and well

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72 Jerry Grey, ***Enterprise*** pp 66-68.

73 ***Ibid.*** p 66.

versed in the political process, was an 'ardent and effective instrument in combating the suddenly powerful anti-shuttle movement'.[74] As in the House, the debate in 1970 was crucial and opposition was at its height, as Glen Wilson recalled:

> We came awfully close to losing the damn thing. ... We won that first shuttle go-around by four votes, [32-28].[75]

Mondale and Proxmire continued their attack during the Appropriations Bill in December 1970, but eventually lost by a large margin, 50-26, allowing NASA's space station/shuttle programme to go through the Senate.

In the years between 1968 and 1970 neither strong advocates nor influential opponents of the civilian space programme successfully dictated the political agenda. Public and political support for any new space programme on a similar scale to Apollo was, at best, indifferent. Those that exhorted the development of the space station and shuttle were successful only in negotiating for further research into the possibilities. Although funding for the Apollo applications programme, which would utilize the remaining Apollo hardware in near-earth orbit, had been secured, the prospects for NASA's space station and shuttle were bleak.

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74 ***Ibid.*** p 69.

75 Glen Wilson, quoted in ***Ibid.*** p 69.

Two *Space Shuttle Program Requirements Documents* were issued in 1970, which summarized NASA's specifications for the shuttle as the programme transferred to Phase-B. Following the Phase-A effort, the shuttle's configuration had congealed into a fully reusable two stage vehicle, with the orbiter housing a 15 foot diameter, by 60 foot long payload bay. The vehicles lifting capability was specified at 25 000 pounds to the design reference orbit, 270 nautical miles circular with a 55 degree inclination: the location of NASA's proposed space station. Operational capability was expected to begin in the second half of 1977. Total turn around time, from landing to launch readiness, was dictated at less than two weeks, and launch rates predictions varied from a minimum of 25 to a maximum of 75 per year.[76] By 1974 revision numbers six and seven of the *Space Shuttle Program Requirements Document* were describing a very different technological system:

> The Space Shuttle System flight hardware shall consist of a reusable Orbiter Vehicle including installed main engines, an expendable External Tank and reusable Solid Rocket Boosters which will burn in parallel with the main engines.[77]

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76 NASA, ***Space Shuttle Program Requirements Document Level 1***, Office of Manned Space Flight, July 1, 1970 (NASA History Office Archive, Washington DC); NASA, ***Space Shuttle Program Requirements Document Level 1: Change No. 2***, Office of Manned Space Flight, December 3, 1970 (NASA History Office Archive, Washington DC).

77 NASA, ***Space Shuttle Program Requirements Document Level 1: Revision No 6,*** Office of Manned Space Flight, March 12, 1974 (NASA History Office Archive, Washington, DC), p 1; NASA ***Space Shuttle Program Requirements Document Level 1: Revision No.7***, Office of Manned Space Flight, October 7, 1974 (NASA History Office Archive, Washington, DC), p 1.

The justification for the shuttle had also expanded, from an initial objective, 'to provide a low-cost, economical space transportation system'[78] to include 'a capability designed to support a wide range of scientific, defence, and commercial users'.[79] Launch rates had been quietly dropped and the operational date had been deleted altogether. Within three years both the design of the shuttle and the programme's underlying rationale had shifted. In the next chapter the events, processes and interactions that led to these changes are revealed.

78 NASA, ***Space Shuttle Program Requirements Document Level 1*** p 1.

79 NASA, ***Space Shuttle Program Requirements Document Level 1: Revision No.7*** p 1.

Chapter 3

Redefinition

> Technical people rely upon their ties with power because it is the access to that power, with its huge resources, that allows them to dream, the assumptions of that power that encourages them to dream in an expansive fashion, and the reality of that power that brings their dreams to life.[1]

Internal Dissidents.

The plans of the Office of Manned Space Flight were not only being frustrated by external factors. Internal obstacles also appeared as factions within NASA mobilized their forces in an attempt to capture control of the shuttle programme's resources.[2] At the end of 1969 no firm consensus existed between, or within, the NASA Centers about a shuttle design. Supporters for partially or completely recoverable versions of the Saturn rocket and some minor patronage for a single stage to orbit vehicle could still be found.[3] Advocates for further development of lifting body technology could also be discovered at the Flight Research Center and the Office of Advanced Research and Technology.[4] The greatest pressure though, came from

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1 David Noble, ***Forces of Production: A Social History of Industrial Automation*** (New York, Alfred Knopf, 1984), p 44.

2 Adelbert Tischler, letter to the author, April 16, 1996.

3 Dennis Jenkins, ***Space Shuttle*** p 67.

4 Adelbert Tischler, letter to Author, April 16, 1996.

the Johnson Space Center. NASA's FY 1970 budget had allowed $30 million for the already awarded Phase-B studies,[5] Johnson, however, wanted additional funding to explore alternative concepts.

Max Faget, the Mercury capsule designer, was leading a group of renegade engineers in an attempt to influence the Office of Manned Space Flight to develop a small interim shuttle to test the concept of a logistics system. Embarking on an in-house study in January 1970, their philosophy was to design a system that would lower both developmental costs and risks.[6] Known as the DC-3 because of its relative simplicity,[7] the design was much smaller than those being considered by the Office of Manned Space Flight. But despite his efforts Faget did not find much support for his ideas.[8] The Office of Manned Space Flight favoured building a large scale shuttle that would qualify immediately as an operational system.[9] From the outset the Office of Manned Space Flight thought it would be dangerous to build a research vehicle and then go back to Congress to

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5 William Normyle, 'NASA Asks Quick Shuttle Replies,' ***Aviation Week and Space Technology*** (February 23, 1970), pp 16-17.

6 LeRoy Day, interview with author, June 29, 1995; Robert Thompson, interview with author, September 7, 1995; 'Mini Shuttle Proposed as Interim Project,' ***Aviation Week and Space Technology*** (February 23, 1970), p 16.

7 It was named after the Douglas DC-3 aeroplane, which had become renowned for reliability and simplicity of design.

8 Max Faget, interview with author, September 9, 1995.

9 Letter to Adelbert Tischler from George Mueller, August 25, 1969 (NASA History Office Archive, Washington DC).

ask for more money to construct an operational vehicle, as LeRoy Day recalled:

> Making the shuttle smaller would not make the development of the technology any easier.[10]

Nevertheless, a realization that NASA's budget was not going to be restored to the heights of Apollo slowly filtered through the organization. NASA Administrator, Thomas Paine, thus agreed to establish a separate Phase-A effort in the event that budget limitations forced NASA into a redesign.[11]

Proponents of the large fully reusable two-stage shuttle also began to seek alternatives that would allow them to continue with their design and reduced peak funding. Two versions of the same idea, one advanced by Marshall's former director, Wernher von Braun and the other proposed by the new Associate Administrator for Manned Space Flight, Dale Myers, involved spreading the development costs over a longer period by phasing the programme.

Von Braun started his campaign early in an attempt to persuade top NASA officials that the agency should develop the reusable booster first, thus allowing NASA to go operational with an expendable orbiter while the reusable

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10 LeRoy Day, interview with author, June 29, 1995.

11 Richard Kline, interview with author, May 31, 1995; William Normyle, 'NASA Asks Quick Shuttle Replies,' ***Aviation Week and Space Technology*** (February 23, 1970), pp 16-17.

version was under development.[12] The concept did gain credence within certain sections of NASA. Milton Thompson, from the Flight Research Center, described the idea as:

> not only ... the most attractive alternative, but also the most logical.[13]

Von Braun and his advocates considered that if NASA did develop the reusable booster first, then not only would it provide a proof of concept, but the next logical step would be to build the reusable orbiter.[14]

It was during a meeting on November 27, 1970, at the home of NASA's Deputy Administrator, George Low, that Myers suggested 'a course of action in which the orbiter might be developed for initial operational readiness using an expendable Saturn-IC booster.'[15] For Myers it was clear that the development of the orbiter first was the logical path to take because 'it focused all the attention on the toughest technology problem.'[16]

George Low had received a similar suggestion from the Aeronautics and Space Engineering Board as they expressed feeling 'uneasy about the apparent inflexibility in the

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12 Letter from Dale Myers to Thomas Paine, June 29, 1970 (NASA History Office Archive, Washington DC).

13 Letter from Milton Thompson to Dr W. Von Braun, November 18, 1970 (NASA History Office Archive, Washington DC).

14 *Ibid.*

15 Charles Donlan, memorandum for the record, discussion of the space shuttle program with Dr. Low,' December 2, 1970 (NASA History Office Archive, Washington DC).

16 Dale Myers, quoted in Zack Strickland, 'Expendable Booster Gains Favor As NASA Studies Phased Shuttle,' ***Aviation Week and Space Technology*** (June 21, 1971), p 19.

original concept of the shuttle.'[17] Seeing its role as an engineering advisory body, the Aeronautics and Space Engineering Board went on to recommend:

> If future payloads decrease in size and frequency, the trade off between initial R&D and operating costs may suggest a different approach ... Thus, an "interim" booster system might be satisfactory for several years.[18]

George Low reassured the Aeronautics and Space Engineering Board that NASA was:

> looking at a number of ways to minimize technological risk and to decrease peak annual funding.[19]

These included an interim booster as part of a phased approach to the shuttle's development, but Low was still unconvinced on its merits and told the Aeronautics and Space Engineering Board that:

> the most promising [expendable interim booster is] the S-IC, the Saturn V first stage. But even the S-IC presents formidable problems. There are technical difficulties, especially in the area of combined vehicle control, and also economic problems arising from the high cost of modifying the SI-C and the high repetitive cost of each launch.[20]

The concept of a phased approach did, however become increasingly attractive within NASA, although the agency found it much harder to sell to the contractors working on

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17 Letter from Raymond L. Bisplinghoff, Chairman The Aeronautics and Space Engineering Board, National Academy of Engineering, to George Low, December 18, 1970 (National Academy of Sciences Archive, Washington DC).

18 *Ibid.*

19 Letter from George Low to Raymond L. Bisplinghoff, National Academy of Engineering, January 11, 1971 (National Academy of Sciences Archive, Washington DC).

20 *Ibid.*

Phase-B. Discussions held at McDonnell Douglas resulted in them recommending 'against any interim booster system' preferring instead 'a slip of a year or so in the launch date.'[21] North American Rockwell 'also presented similar arguments to those heard at the McDonnell Douglas briefing'.[22] North American Rockwell's Shuttle Project Manager, Bastian Hello highlighted the reasoning behind their negative reaction:

> As the programme went on doubts were raised about the R&D costs ... NASA started looking at partially reusable and partially throw-away vehicles ... we thought we were leading the pack ... in the all-reusable design and we were a little reluctant to let go of what we thought was our advantageous perch.[23]

As the programme moved into 1971 the orbiter-first strategy gained more weight. Despite Milton Thompson's observations that NASA had 'some tremendous gaps in the knowledge and experience required to design a successful shuttlecraft, regardless of all our spacecraft and aircraft experience'[24] the booster-first approach was 'never taken seriously by the shuttle program management'[25] and after 1970 gained no further credibility.

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21 Charles Donlan, memorandum for the record, trip report on visit to Phase-B contractors with Dale Myers on December 21, 1970, dated January 4, 1971 (NASA History Office Archive, Washington DC).

22 *Ibid.*

23 Bastian Hello. interview with author, April 27, 1995.

24 Letter from Milton Thompson to Dr W. Von Braun, November 18, 1970 (NASA History Office Archive, Washington DC).

25 Charles Donlan, letter to the author, May 29, 1996.

An Inconspicuous Coup.

Tensions between NASA Administrator Thomas Paine, the Congress, and other executive branch officials had been working against NASA. Constantly agitating for additional funding, Paine publicly criticized the Nixon Administration for cutting NASA's budget.

> Battling everyone in the executive branch from mid-level Office of Management and Budget personnel to the president, he proved an embarrassment to the White House and soon lost credibility with the administration.[26]

After the Space Task Groups recommendations were ignored by the White House, Paine decided to resign from the post of NASA Administrator.[27] The Nixon Administration's refusal to support NASA's post-Apollo planning reinforced Paine's belief that, as a Democrat, he was an outsider within the new Republican Administration.

> I sat down with Nixon always under rather formal and stilted circumstances. But he gave every appearance of listening and interacting and I would say, looking back on my interactions with the White House at that time, that I finally left because I really didn't think I could deliver to NASA the kind of relationship the head of NASA really ought to deliver.[28]

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26 Roger Launius, 'NASA and the Decision to Build the Space Shuttle, 1969-72,' ***The Historian*** 57 (Autumn 1994) p 25.

27 Paine actually left office in September 1970 although his intentions were well known within NASA months before. Hans Mark, ***The Space Station*** p 38; W. Henry Lambright, ***Powering Apollo*** p 208. For background on the resignation of James Webb in 1968 and the appointment of Thomas Paine see pp 201-202, 204, 206-207.

28 Thomas Paine, quoted in Trento Joseph. ***Prescription for Disaster: From the Glory of Apollo to the Betrayal of the Shuttle*** (New York, Crown Publishers Inc, 1987), p 94.

Deputy Administrator George Low was thus placed in the position of Acting Administrator at a crucial juncture in the organizations history.

> Low then led what was a very interesting exercise ... he said we have got make a choice, whether to do the space station first or the shuttle first. ... Technically the space station was easier but, we recognized that the shuttle was the pacing item in this thing and, therefore, we said look ... let's do the difficult thing first and the space station will follow.[29]

> It was clear that the Station would be very expensive using expendable launch vehicles to build ... so it was deferred until the Shuttle was assured.[30]

Initially this idea was treated with some scepticism, as future NASA Administrator, James Fletcher reflected:

> When we first began thinking about the Space Shuttle, we thought of it as a vehicle to serve a large space station in Earth orbit. But we ran into a dilemma: we found that we could not expect to get funding to build both a large space station and the Space Shuttle in this decade. A space station would be of no use without the Shuttle. And at first we thought that the reverse was also true - that the Shuttle would be of little use without a space station to serve. But the more we looked at this, the clearer it became that no dilemma existed but rather an opportunity.[31]

As NASA's programmatic plans were remodelled, justifications for the shuttle became more elaborate. The predominant rationale for the shuttle had been based upon

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29 Hans Mark, interview with author, September 8, 1995.

30 Robert Freitag, letter to the author, June 1, 1996.

31 James Fletcher, banquet address before the Antelope Valley Board of Trade, ***Where Do We Go From Here in Space?***, Lancaster, California, October 18, 1974 (NASA History Office Archive, Washington DC), p 9.

a perceived requirement for a new logistics vehicle for a space station. Now that hardware development of the space station had been postponed the role of the shuttle needed to expand. As well as a service vehicle for a future space station, the shuttle would also be configured to build it.[32] Early conceptual thinking had characterized the shuttle's operational goals as 'broad' and able to serve 'a large number of users'.[33] Revitalized, these justifications now served as the key to the shuttle's promotion. During a meeting on November 27, 1970, top NASA officials, agreed that:

> [NASA] should probably change the baseline mission for the shuttle ... [from] the 270 nautical mile orbit and 55 degrees which is primarily for the space station to something more representative of the needs of NASA and DOD. This step would uncouple the prime justification of the shuttle as support for the space station to one of a transportation system for space satellites.[34]

The shuttle, now unhinged from the space station, was touted as a utilitarian space vehicle that would usher in a new age of space transportation. Economical and routine access to space were now central agents in the advancement of the shuttle.

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32 The shuttle was always a key to the space station and the shuttle's systems and configurations were driven, in part, by the station's requirements. Robert Freitag, letter to the author, June 1, 1996.

33 LeRoy Day, abstract to a collection of papers presented at ***The Space Shuttle Symposium***, October 16-17, 1969 (Smithsonian Museum of Natural History, Washington DC).

34 Donlan Charles, memorandum for the record, discussion of the space shuttle program with Dr. Low, December 2, 1970 (NASA History Office Archive, Washington DC).

> If we had a vehicle that provided a less severe launch environment, adequate space and weight carrying capability, and particularly the ability to return spacecraft to earth for maintenance, repair and refurbishment for reuse, I believe we could move far in the direction of bringing these costs down substantially, and relaxing many of the current constraints on space operations. We have every reason to believe that the Space Shuttle will do just that.[35]

To emphasise the impact the shuttle would have on future space operations, Myers went as far as to suggest the possible savings the shuttle would bring:

> With the largest and most efficient present launch vehicles, the present cost is somewhat under $1,000 a pound. With the Space Shuttle, we expect to get this down to less than $100 a pound.[36]

This statement eventually proved controversial and was based only on preliminary analysis coming from Mathematica, the organization contracted to conduct a cost-benefit analysis of the shuttle. It stirred up a debate both within and outside of the political forum that continued throughout the programme and placed the economic rationale in jeopardy.

An understanding that the economic argument might prove tenuous was appreciated by George Low. Indeed true to Mueller's vision, importance for Low was in the new capabilities that the shuttle would provide.

> NASA is not seeking to justify the space shuttle program on purely economic grounds. The principal

35 Dale Myers, statement at the hearings before The Committee On Science and Astronautics ***1972 NASA Authorization*** (US House of Representatives, US Government Printing Office, 1971) p 136.

36 ***Ibid.***

> justification for the space shuttle is the new capability it can bring both to our civilian and military space programs for versatile and efficient operations in space.[37]

Routine access to earth orbit was seen as the catalyst for future infrastructure building in space.

> George Low, when we started this program, had a vision of making NASA more relevant and that relevancy would come when we had a whole new group of customers, and these would be the entrepreneurs and the cheap experimenters and the Edisons of their time, and we would provide them, easy, cheap access to space and they in turn would come up with new industries.[38]

After Paine's resignation Low, 'attempted to heal the breach between NASA and other agencies in the executive branch'[39] while simultaneously embarking upon a potent campaign for the shuttle. The aftermath of the 1970 Congressional battle left NASA in the role of appeaser. George Low aimed to win the Congress over by arguing that NASA's requests were moderate. Earth orbital hardware development was restricted to the Apollo Applications Program, with space station hardware downgraded to Skylab. The concept of a permanent 100 manned orbiting platform was tabled as a 'future project'.[40]

> We believe that in moving toward the decision on the development of the space shuttle, NASA is

37 Letter to Clinton Anderson from George Low, May 28, 1971 (NASA History Office Archive, Washington DC).

38 Francis Hoban, interview with author, May 15, 1995.

39 Roger Launius, 'NASA and the Decision to Build the Space Shuttle, 1969-72' p 26.

40 Letters to Walter Mondale and William Proxmire from George Low, September 28, 1970 (NASA History Office Archive, Washington DC).

> proceeding in a conservative manner ... In connection with the decisions on FY 1972 budget request, we have deferred the development of the space station to avoid what would other wise have been unrealistic funding peaks during the 1970s.[41]

In an effort to rebut the criticisms of Senators William Proxmire and Walter Mondale, who were attempting to focus an anti-large space programme sentiment in both Congress and the White House, Low emphasised that Mars was not the hidden agenda. He also stressed that:

> the space shuttle program does not represent a commitment to a ***huge manned space program***. ... The space shuttle can be justified by its potential contributions to programs relying entirely on unmanned spacecraft. Decisions on future manned space programs ... can and have been decoupled from the decision on the space shuttle.[42]

Upgraded in status as NASA's principal programme for the 1970s, the shuttle 'became more and more important relative to the other elements'[43] of the space programme. Although a shuttle configuration that could be accepted by all interest groups was yet to be established, the decline of the space station advanced the ascension of a new shuttle principality.

41 Letter to Walter Mondale from George Low, April 28, 1971 (NASA History Office Archive, Washington DC).

42 Letter to Clinton Anderson from George Low, May 28, 1971 (NASA History Office Archive, Washington DC), emphasis in the original.

43 Hans Mark, ***The Space Station*** pp 39-40.

Precarious Affiliations.

Left at the end of 1970 with no human missions beyond the Apollo Applications programme and concerned by the Office of Management and Budget's emphasis on cost-effectiveness, NASA believed that in order to gain political approval, it had to show that the shuttle could perform a much larger role than they had originally intended. NASA thus embarked on a campaign to persuade other communities of the benefits of its new launch vehicle; especially the national security community whose space hardware were projected to constitute some 34 per cent of all future space traffic.[44]

Since the establishment of NASA, the United States has had two space programmes; a civilian one, housed in NASA, and a military one controlled by the Air Force. NASA's long relationship with the US Air Force has invariably been both confrontational and cooperative. In the race for space among the services during the post-Sputnik months of 1957/58, the Army, Navy, and the Air Force all had their long-range space programmes on the table. The Air Force saw space power as 'merely the cumulative result of the evolutionary growth of air power' and, space flight as the 'natural and logical extension of air flight.'[45] General Bernard Schriever, commander of Air Force Systems Command,

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44 John Logsdon, 'The Decision to Develop the Space Shuttle,' ***Space Policy*** 2 (May 1986), pp 103-119; John Logsdon, 'The Space Shuttle Program: A Policy Failure?' ***Science*** (May 30, 1986), pp 1099-1105.

45 John Logsdon, ***The Decision To Go To The Moon*** pp 28, 30.

was convinced long before the launch of *Sputnik I* that 'nations will fight the battles of the future in space'.[46]

Although left out of the competition to launch the first American satellite, the failure of the Navy's Vanguard rocket and the transfer of the Army Ballistic Missile Agency to NASA in 1960 solidified the Air Force's hold on military space flight.[47] The Air Force, however, considered that a programme split between themselves and NASA was unworkable. They lobbied hard in both the Pentagon and the Congress during the early 1960s to gain dominion over human space flight. 'Soviet men in space posed an "impending military threat" that could not be met by current space organization,' argued an Air Force Space Study Committee in 1961. Its recommendation was that a new Air Force Command should 'be given the task of developing manned space flight.' Submerged in rhetoric of space as a "sanctuary", exploited only for peaceful purposes and scientific advancement, arguments for total military control over space operations failed to dislodge NASA's hold over the Lunar landing programme.[48] The Air Force were not however, pushed out of the game entirely. As the Moon landing programme progressed, the transfer of Air Force technology (the Atlas and Titan rockets) and personnel to

46 J. Manno, 'The Military History of the Space Shuttle,' ***Science for the People*** (September/October, 1983), p 7.

47 Walter McDougall, ***The Heavens and the Earth*** pp 197-200.

48 ***Ibid.*** pp 312-324.

NASA impacted significantly on the space agency's culture, management systems, and relationship to the service.[49] The Air Force continued to fund research projects for human space flight during the 1960s, but the termination of its spaceplane, Dyna-Soar in 1963 and the cancelation of the Manned Orbital Laboratory in 1969, had left the Air Force hesitant over its role within a national space programme.

Despite this the Air Force had demonstrated an interest in NASA's space station/shuttle development programme. Although their research was being conducted separately, there was some cooperative agreement between the Air Force and NASA in generating shuttle concepts during 1969.[50] The framework for DOD participation in NASA's shuttle programme was established through two groups: the Aeronautics and Astronautics Coordinating Board and the Space Transportation System Committee. The Aeronautics and Astronautics Coordinating Board had been in existence since 1965 and served primarily as a mechanism for the formulation of policy. During 1969 the issues on the Aeronautics and Astronautics Coordinating Board's agenda were: the progress of NASA's shuttle design; establishment of DOD design requirements and their impact on NASA's plans; and the interrelationship between DOD's

49 Howard McCurdy, ***Inside NASA: High Technology and Organizational Change in the US Space Program*** (Baltimore: The John Hopkins Press, 1993), pp 14-17.

50 This was, in part, due to the fact that the aerospace companies working for the Air Force were the same four under contract with NASA: General Dynamics, Lockheed, McDonnell Douglas, and North American Rockwell. 'Air Force Pushing Studies of Reusable Space Shuttle,' ***Aviation Week and Space Technology*** (August 11, 1969), p 25.

current fleet of expendable launch vehicles, their growth versions, and a reusable launch vehicle. The Space Transportation System Committee was signed into existence on February 17, 1970 and was co-chaired by Grant Hansen, Assistant Secretary of the Air Force for R&D, and Dale Myers, NASA's new Associate Administrator for Manned Space Flight. The committee had a broad mandate to review shuttle operational plans, technology requirements, programme objectives, and development plans to ensure that both NASA and DOD specifications could be met.[51]

Cooperation in developing concepts for a reusable space vehicle between the Air Force and NASA had begun in 1966. At the time it was concluded that the numerous cost uncertainties and technical risks could not be resolved. Their report did, however, consider that future demand for access to space would encourage the development of reusable launch vehicle technology and, that the current (1966) launch vehicle system would only fulfil NASA and DOD requirements for the next 7 to 10 years.[52]

The DOD did, however, view a NASA operated shuttle as potentially useful. The promise of lower costs to access space combined with the potential of new capabilities proved an attractive prospect. The Air Force though, were not prepared to fund any part of the programme from its own

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51 Scott Pace, ***Engineering Design and Political Choice*** pp 100-101.

52 ***Report of the Ad-Hoc Subpanel on Reusable Launch Vehicle Technology***, September 14, 1966 (NASA History Office Archive, Washington DC), pp 1-8.

budget. Secretary of the Air Force Robert Seamans admitted that he saw 'no pressing need for the shuttle' but did characterized it as 'a capability the Air Force would like to have'.[53] Seamans was a former NASA top official, and sympathetic to the agency's aspirations. Few other high ranking Air Force officers favoured the shuttle and were content with their expendable launchers like the Atlas and Titan.[54] Hansen best summed up the position.

> Sure, NASA needs the shuttle for the space station ... but for the next ten years expendables can handle the Air Force job. We won't seek shuttle funds even if NASA doesn't. We don't consider the shuttle important enough to set money aside for it.[55]

The job of securing Air Force support had become paramount for NASA if the economic arguments given to the White House and the Congress were to stand ground. Before 1971 drew to a close, NASA's efforts to gain the Air Force as an ally would have a significant impact on a shuttle design.

Three key shuttle requirements were insisted on by the Air Force at the end of Phase-A: lifting capability, orbiter payload bay size and orbiter crossrange (the lateral manoeuvrability of an aircraft). The dimensions of the payload bay and the lifting capability of a shuttle

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53 John Logsdon, 'The Decision to Develop the Space Shuttle' p 109.

54 Bill Sneed, interview with author, August 21, 1995.

55 Quoted in Jerry Grey, ***Enterprise*** p 68.

were based on a new generation of DOD reconnaissance satellites. Far heavier and larger than any previous observation satellites, it was lifting these kinds of payloads that the Air Force saw its most frequent use of the shuttle.[56] In a presentation to the NASA on June 29, 1970, the Air Force discussed DOD payload size and weight requirements. DOD satellite designs for the 1970s dictated a vehicle configuration which would could accommodate a payload of 10 feet in diameter 60 feet in length, and be able to launch up to 30 000 pounds into a near-Earth polar orbit. Given the drivers of improved capabilities, increases in power, and extensions of lifespan, Air Force projections for the 1980s required a shuttle capable of lifting payloads between 40 000 to 50 000 pounds to the same orbit, within a 15 feet diameter by 60 feet long payload bay.[57]

LeRoy Day's Space Shuttle Task Group had not specified any volume requirements in its 1969 report. A design goal of lifting 55 000 pounds to a space station was unofficially stipulated by the Office of Manned Space Flight during a briefing with the Phase-A shuttle contractors and a maximum diameter of 22 feet for the

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56 Joining the separate functions of area surveillance and close-look photography into one satellite was responsible for the increased size and weight of this new system. Increasing the length of the satellite made possible increases in focal length of the camera, which when combined with increases in the camera aperture provided new a new level of ground resolution. T. Greenwood, 'Reconnaissance and Arms Control' ***Progress in Arms Control?*** (San Francisco: W.H. Freeman and Co, 1979), p 99.

57 The increase in diameter represented early thinking within the Air Force on the size of a third stage, or space tug that would deliver satellites to higher synchronous orbits.

payload bay had been examined by some of the contractors in 1969. As the Phase-A studies progressed, shuttle designs incorporated payload weights of between 25 000 and 65 000 pounds, and payload diameters of either 15 or 22 feet, at a variety of lengths.[58] The Office of Manned Space Flight eventually specified a 15 foot diameter by 60 foot long payload bay in the summer of 1970.[59] A statement of work, issued in February 1970, indicated a desired lifting capability of 15 000 pounds to the reference orbit for a space station, but this was later revised to 25 000 pounds.[60]

Crossrange requirements arose from a tactical judgement. The Air Force wanted an orbiter that could rendezvous with a satellite and return to Earth after completing only one orbit, thus removing the need for flying over hostile territory in times of crisis. This demanded a high-crossrange capability of between 1100 and 1500 nautical miles on either side of the orbiter's reentry ground track. A requirement that arose from the physical reality that the landing strip would have moved east some 1100 miles as the Earth rotated during the shuttle's first orbit. This requirement for a return to runway after a

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58 Scott Pace, ***Engineering Design and Political Choice*** pp 111-113.

59 ***Space Shuttle Program Requirements Document Level 1***, Office of Manned Space Flight, July 1, 1970 (NASA History Office Archives, Washington DC), p 2.

60 ***Space Shuttle Program Requirements Document Level 1, Change No.2***, Office of Manned Space Flight, December 3, 1970 (NASA History Office Archive, Washington DC), p 5.

single orbit dictated a relatively shallow angle of attack and the high lift of a delta wing. In a series of reports the Air Force also argued that a delta wing planform would produce a more aerodynamically stable and thus far safer orbiter.

Nonetheless, crossrange was of no great concern to some of NASA's engineers. Their primary interest was providing a routine daily opportunity to return to the Kennedy Space Center, which only demanded a low 200 nautical mile crossrange capability. Many of the orbiter configurations emanating from Johnson, the NASA Center that traditionally controlled spacecraft design, thus adopted straight wings, essentially for simplicity. Indeed as Max Faget, a leading spacecraft designer at Johnson recalled several Johnson engineers were:

> dead set against the [high] crossrange, it cost us a lot on performance. Having a [higher] crossrange on the way down meant you had to carry a heavier vehicle up there, and that extra weight on the vehicle meant less payload.[61]

Advocates of the low crossrange design also claimed that the Air Force did not appreciate NASA's expertise in low-lift-to-drag ratio wing designs that used exceptionally high angles of attack; a critical point in safely operating a straight winged orbiter.[62] Arguments for a straight

61 Max Faget, interview with author, September 9, 1995.

62 Scott Pace, ***Engineering Design and Political Choice*** pp 111-113; Dennis Jenkins, ***Space Shuttle*** pp 67-69.

winged orbiter were, nevertheless, wholly rejected by the Air Force.

The controversy over crossrange continued on through 1970 because the Office of Manned Space Flight failed to generate any decision on the subject. Indeed both the 200 nautical mile and 1500 nautical mile crossrange options were still included in a second Office of Manned Space Flight shuttle requirements document released in December 1970.[63] Awareness of the political and economic conditions, however, obliged NASA to formally adopt all Air Force requirements into its Phase-B studies, early in 1971. The manoeuvre was essentially a political one. NASA needed Air Force support to strengthen the shuttle's economic rationale and so gain political sanction. The straight wing approach was, therefore, dropped in favour of a delta-wing design, which would produce the Air Forces stipulated 1500 nautical mile crossrange; and the large 15 X 60 foot payload bay and a system lifting capability of 65 000 pounds into a due east orbit, the Air Force's two other principal requirements, were also incorporated. The extent of the Air Force's influence on NASA to adopt these requirements at this time is, however, debatable.

> As we got into Phase-B we had pretty well established, although there was still a lot of debate, ... the 15 foot diameter, 60 foot long payload bay. We had pretty well established the roughly 20 ton, 60 000 pounds due east orbit. ...

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63 ***Space Shuttle Program Requirements Document Level 1, Change No.2***, Office of Manned Space Flight, December 3, 1970 (NASA History Office Archives, Washington DC), p 3.

> We played with cutting the payload bay size down, we played with cutting the crossrange down, ... but I don't think we ever deviated very much from what we built as far as payload bay and crossrange requirements were concerned.[64]

The 15 X 60 foot payload bay and the 65 000 pounds lifting capability had become more important to NASA since the postponement of the space station. Still on NASA's planning boards, the eventual construction of the space station would dictate a launch vehicle configuration that could contain and lift each of the modules into orbit.[65]

In line with Nixon's original request to former NASA Administrator Thomas Paine, to cut NASA's human space flight budget in half, NASA had come to the conclusion in early 1971 that by postponing the space station they could continue with the reusable two-stage shuttle at a development cost of $12 billion.[66] The National Academy of Engineering, however, were still troubled by the proposed development cost of NASA's shuttle, as the following letter extract shows:

> Basically, I'm afraid our concern today, as it has been in the past, is that the justification of the space shuttle program is still weak. It appears to us that the reason for this weakness

64 Robert F. Thompson interview with author, September 7, 1995.

65 The 15 X 60 foot payload bay would be large enough to house one module, and the 65 000 pound lifting capability to a 100 n.m. orbit translated into 25 000 pounds to NASA's reference orbit for a space station. Robert Freitag, letter to the author, June 1, 1995.

66 Hans Mark. interview with author, September 8, 1995.

> is not so much the ultimate utility of the system but the fact that we still have not found the way to spread out the development costs in order not to have such a tremendous development peak that the entire NASA budget is placed in jeopardy. In the present environment of the anti-technologists, it seems to us even more important that we somehow solve the cost problem, particularly the development cost impact.[67]

In replying to the National Academy of Engineering, George Low alluded to the shifting position of NASA's higher echelons towards an alternate shuttle system:

> Spreading out the development costs of the shuttle so as not to place the NASA budget in jeopardy has been a subject of concern both to NASA and to our Phase-B shuttle definition contractors. We are devoting a great amount of study to cost reduction and cost alternatives. ... As part of our Phase-A activity, we have under study several alternate concepts for the space shuttle.[68]

Shifts in the Baseline Design.

The preferred orbiter configuration to emerge from the Phase-B and alternate Phase-A studies was a delta wing vehicle, which incorporated external liquid hydrogen fuel tanks that could be jettisoned before entering orbit (see figure 3:1).[69] The incorporation of external fuel tanks allowed for a simplification of the orbiter's design, with

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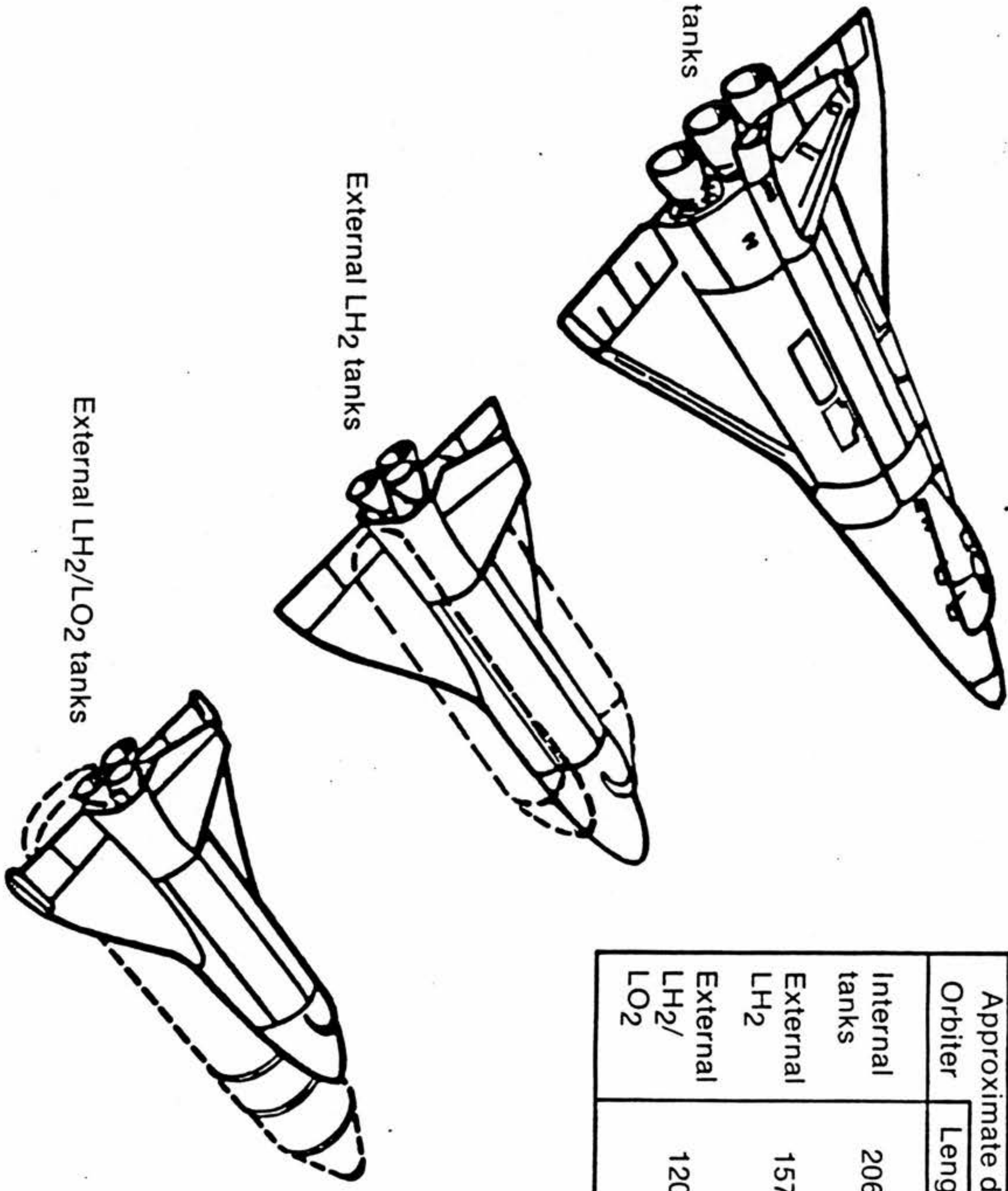
67 Letter from Raymond L. Bisplinghoff, National Academy of Engineering, to George Low, April 22, 1971 (National Academy of Sciences Archive, Washington DC).

68 Letter to Raymond L. Bisplinghoff, Chairman The Aeronautics and Space Engineering Board, National Academy of Engineering, from George Low, May 21, 1971 (National Academy of Sciences Archive, Washington DC).

69 Letter from James Fletcher to Dr O'Brian, June 16, 1971 (NASA History Office Archive, Washington DC); Letter from James Fletcher to Robert Seamans, June 16, 1971 (NASA History Office Archive, Washington DC); Strickland Z. 'Expendable Booster Gains Favor As NASA studies Phased Shuttle' ***Aviation Week and Space Technology*** (June 21, 1971) p 19.

Figure 3:1.

Source: NASA History Office Archive, Washington DC.



Approximate dimensions - ft		
Orbiter	Length	Wing span
Internal tanks	206	107
External LH_2	157	97
External LH_2/LO_2	120	80

- Orbiter comparison.

the overall size of the orbiter now being driven by the payload bay rather than the size of the internal tanks. Removal of the orbiter's internal fuel tanks represented the most significant deviation from NASA's original shuttle design and paved a way for NASA to manoeuvre around both the political and economic obstacles that stood in the way of the shuttle's development. Space Shuttle Program Manager, Robert F. Thompson considered the removal of the fuel tanks from the orbiter as 'the single most important configuration decision made in the shuttle program.'[70]

> I think the biggest thing that broke [the] logjam was our willingness to give up on everything being reusable. To take the propellants out of the orbiter. Propellants just made a mess out of trying to build the orbiter. You get them out and get them in a fairly simple tank, get some great big manifolds there to pump the propellant through and then throw that aluminum tank away, looked like a good common sense way of going.[71]

Once NASA's higher echelons conceded to the idea of merging expendable technology with reusable, a shuttle design which proved politically acceptable shortly followed.

The idea was most forcefully put forward in proposals from Grumman Aerospace. Grumman, who were working on the alternate Phase-A studies, had been persuaded by some early ideas emanating from Johnson, as Grumman's Shuttle Engineering Manager, Richard Kline recollected:

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70 Robert Thompson, ***The Space Shuttle: Some Key Program Decisions***, American Institute for Aeronautics and Astronautics, Von Karman Lecture, 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 1984 (supplied to the author by Robert Thompson), pp 3-4; Michael Yaffee, 'Program Changes Boost Grumman Shuttle' ***Aviation Week and Space Technology*** July 12, 1971), pp 36-39;

71 Robert Thompson, interview, with author, September 7, 1995.

> When we heard those we felt that really was the answer. Not the technical answer but the pragmatic answer in view of the financial restrictions. So we went after the external tank concept quite heavily and validated the practicality of doing that.[72]

A series of design reviews conducted during January and March 1971, indicated that significant advantages could be made if the orbiters liquid hydrogen fuel tanks were an external structure. The innovative move by Grumman was to extract the orbiter's liquid hydrogen tanks, which were far larger than the liquid oxygen tanks, and place them externally either side of the payload bay. The concept allowed the orbiter to shrink in size, thus altering the energy balance between the orbiter and the booster. Further studies by both NASA and the shuttle contractors demonstrated that additional savings in development costs could be made if both the liquid hydrogen and the liquid oxygen tanks were housed in a single external tank structure. In August 1971, the introduction of a single external structure housing both the liquid oxygen/hydrogen tanks for the orbiter had become a NASA baseline design.[73]

To circumvent criticism by the Congress and the White House, NASA's higher echelons publicly announced in June 1971 what they had been considering at the end of 1970: to proceed with phasing the shuttle's development. The orbiter would be developed first followed by the booster. An

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72 Richard Kline. interview, with author, May 31, 1995.

73 Scott Pace, 'Engineering Design and Political Choice,' p 31.

interim, expendable booster would then serve the system while the reusable, human operated booster was under development. NASA argued that this would keep programme peak funding to just under $2 billion.[74] This change in the programme's approach translated into very different set of booster requirements.

Multi-stage rockets had played a vital role in NASA's crusade to the Moon. Staging methodologies provided step-wise increases in velocities with systems of conservative propellant-to-stage mass ratios.[75] Staging the rocket was a practice established very early in the history of space flight. Ultimate stage velocity at burnout is exponentially proportional to the ratio of initial fuel mass to total system mass. Separating the rocket into stages kept the mass ratio of each stage at conservative levels and allowed the final stage velocity (the sum of the velocity increases from each stage) to be tailored for a characteristic final orbit or escape trajectory.[76] The total mass of a space transportation system comprises of propellant, vehicle and payload. Maximising the payload requires minimising the inert vehicle mass that must be carried along with it.

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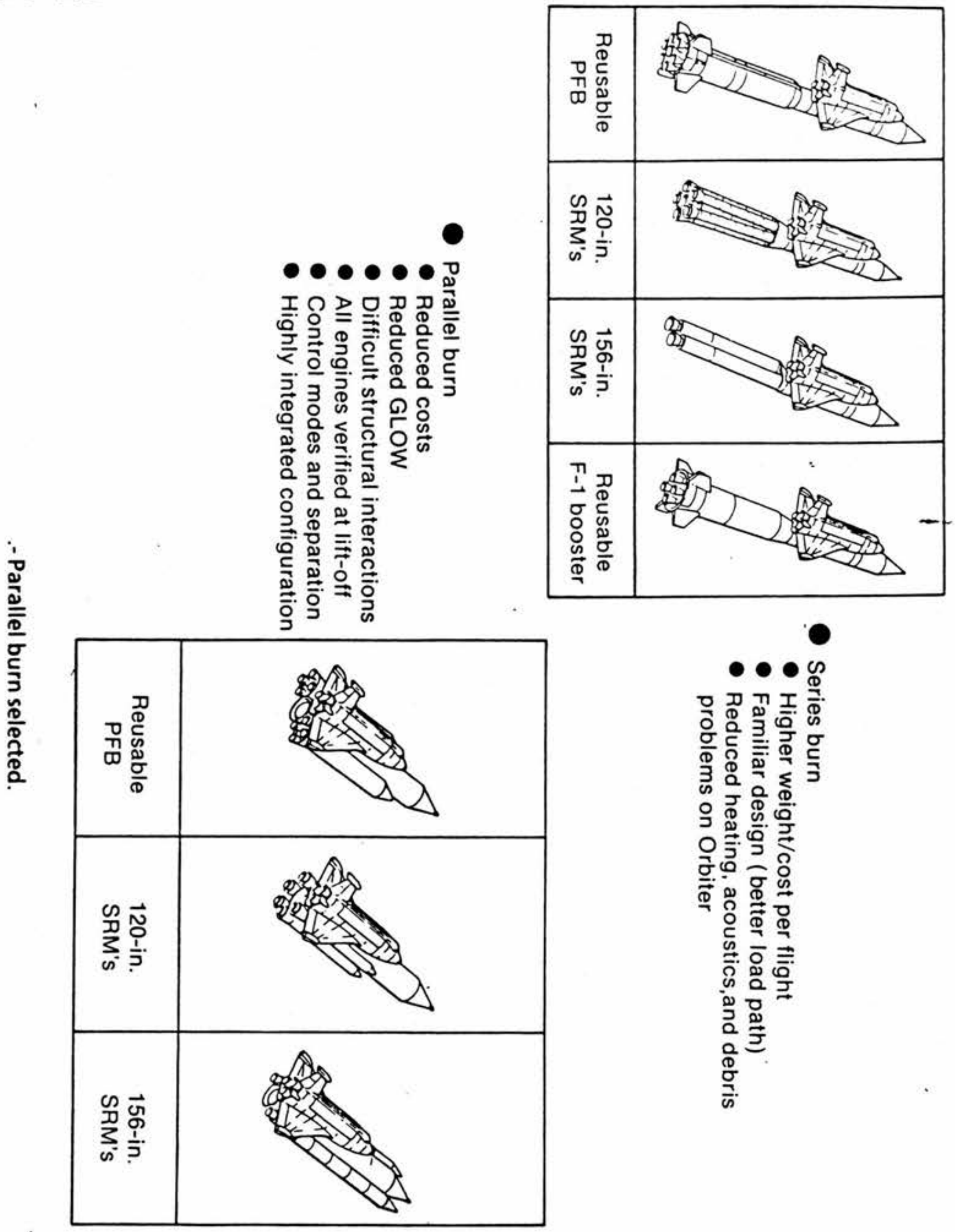
74 Robert Thompson, ***Von Karman Lecture*** pp 3-4; M. Yaffee 'Program Changes Boost Grumman Shuttle' ***Aviation Week and Space Technology*** (July 12, 1971) pp 36-39;

75 Mass ratio is a design parameter which relates the total mass at ignition and the final rocket mass at burn-out.

76 Max Faget. interview, with author, September 9, 1995; Myron Uman. (Electronic mail, October 7, 1996); Adelbert Tischler. interview, with author, May 3, 1995; Adelbert Tischler, letters to the author, November 13 and December 4, 1996; Lyn Dutton. Etal ***Military Space*** pp 30-36; Arthur C. Clark. ***The Exploration of Space*** pp 27-28; Joseph Thiboaux. 'Propulsion and Power Systems Perspective' Norman Chaffee. (ed) ***Space Shuttle Technical Conference, Part 2.*** (Houston Texas, NASA, JSC, Conference Publication 2342, 1985) pp 581-584.

Figure 3:2



Source: NASA History Office Archive.

Nevertheless, there are limitations to reducing the collective mass of a system's structure. The solution was to partially offset this limitation by using several propulsion stages. This amounts to removing the inert mass of each stage when the stage has expended its propellant (and thrust capability), thereby lightening the remaining vehicle.

In 1970, structural design, materials and fabrication techniques were not considered by many of NASA's engineers and their contractors, to be sufficiently advanced to produce a single stage to orbit vehicle.[77] Staging methodologies thus followed on into the shuttle, which is why a vehicle incorporating two separate stages was first considered as the most viable configuration.[78]

When NASA moved to the interim booster approach two sets of staging criteria were evoked: series burn and parallel burn systems (see figure 3:2). Series burn was a known stacking arrangement, traditionally exploited on NASA's previous launch vehicles. Orbital velocity would be achieved via stages, with the booster powering the initial ascent on its own and then, after separation, the orbiter's engines would ignite for the final climb. Three different booster concepts came under consideration within this

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77 Single stage to orbit vehicles are only just recently becoming a distinct possibility with developments in new high-strength, light-weight materials and fabrication techniques. Adelbert Tischler, letter to the author, November 13, 1996.

78 Adelbert Tischler, letter to the author, June 16, 1997.

category: the Saturn I-C as proposed by Dale Myers; a winged version of the Saturn V, proposed by Boeing; and a modified Titan III, proposed by the contractor Martin Marietta. Although NASA favoured the use of the SI-C, David Vine, Vice President of Martin Marietta, lobbied hard for the Titan III. He claimed that the development costs would be low because most of the components were already in production, and that a modified Titan would also provide a basis for active Air Force participation in the shuttle programme.[79] Boeing's idea, to convert the Saturn V into a booster system that could be recoverable after a sea ditch or a human-occupied fly-back vehicle, met with mixed reaction within NASA. Some considered the approach to be pragmatic because it utilized technology already in existence, while others were concerned that such a system would mean that the two-stage, fully reusable shuttle would 'never come to full fruition.'[80]

Parallel burn was a new procedure and presented the 'challenge of a previously untried stacking arrangement.'[81] The concept involved the orbiter's main engines working simultaneously with the boosters allowing both to provide the necessary thrust for lift-off. The stacking arrangement was conducive to the use of relatively low performance

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79 Z. Strickland, 'Titan 3L Studied As Expendable Booster' ***Aviation Week and Space Technology*** (August 2, 1971) pp 40-41.

80 ***Ibid.***

81 Robert Thompson, ***Von Karmen Lecture*** p 8.

boosters as the orbiter's main engines would perform a larger share of the boosting, thus the staging velocity could be reduced to around 3 000-4 000 feet per second. In addition, the parallel burn concept meant that verification of main engine ignition could be made prior to booster ignition.[82] The technical proposals were due on the December 15, 1971, but as late as November NASA was still undecided on whether to opt for a series burn or parallel burn configuration (see figure 3:3 for some comparisons).

Enervation, Resurgence and Ratification.

George Low's role as NASA's acting Administrator ended with the appointment of James Fletcher in March 1971. Fletcher, after a long career in industry as a physicist and as president of the University of Utah, came to NASA with strong Republican credentials. Initially he presented a very cynical attitude towards human space flight and questioned the judgement of NASA's top officials on the need for a shuttle. Within a short time, however, he had become convinced that approval of the shuttle programme was essential.[83] With over $4 billion invested in facilities to support human space flight and NASA's three main Centers, Kennedy, Johnson, and Marshall almost totally dedicated to

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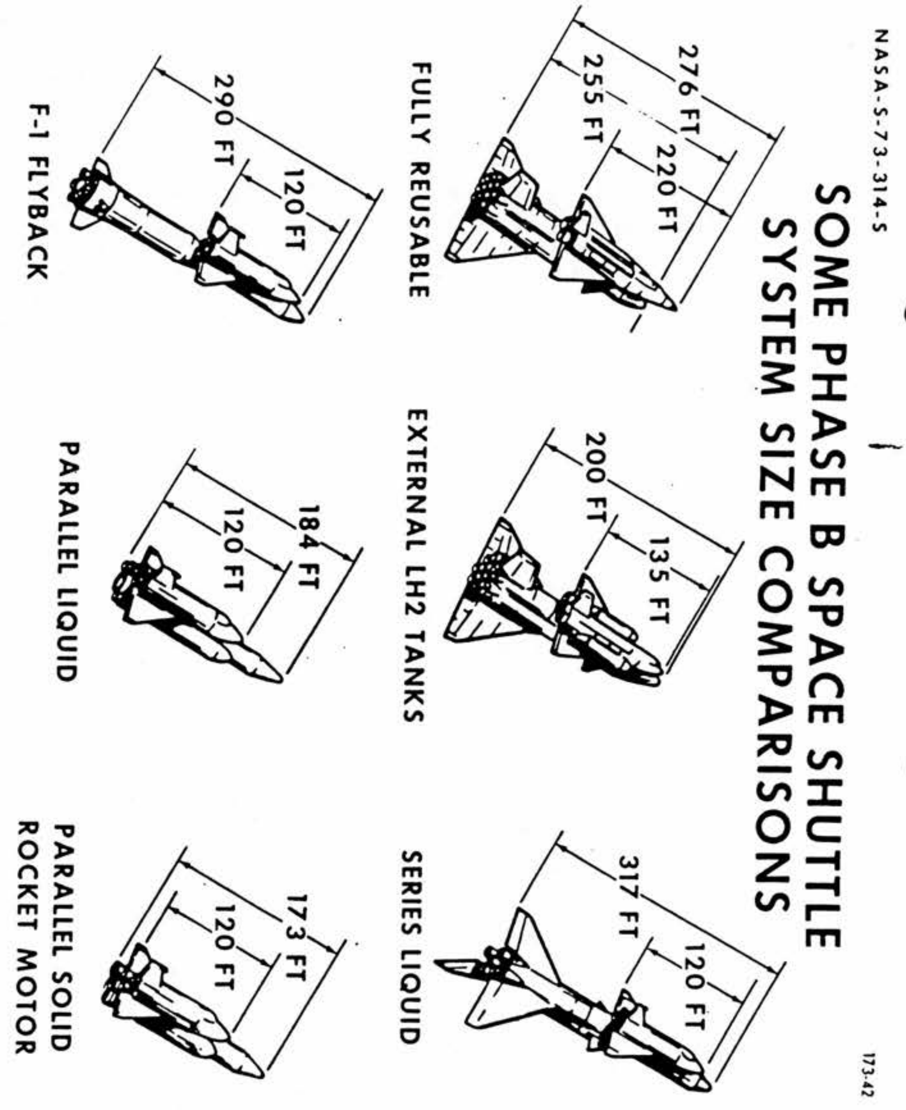
82 NASA. ***Technology Influence on the Space Shuttle Development*** p 5-20.

83 Jerry Grey, ***Enterprise*** p 71; Joseph Trento, ***Prescription for Disaster*** pp 105-106; John Logsdon John, 'Decision to Develop the Space Shuttle,' p 107.

Figure 3:3



- Flight vehicle configuration evolution, Phase B and Phase B extension - 1970 to 1972.

Source: NASA History Office Archive.

it, support was imperative if NASA's organizational structure was to remain intact.

Within Congress, a continuing rise in unemployment was spurring on a campaign for increased public spending. The 1970 recession and the refusal of Congress to hold down public spending meant that the deficit for the fiscal year ending in June 1971 was $23 billion, far more than in any post-war year except 1968. Unemployment was up to 6.1 per cent in May and the dollar had steadily grown more vulnerable in the international exchanges. A flight from the dollar in the money markets grew to rout proportions, finally leading to the Bank of England requesting that the US guarantee convertibility of Britain's dollar holdings into gold. In an attempt to stabilize the economy, on August 15 Nixon made a radical economic policy u-turn reverting to tight controls, including: a ninety day freeze on wages and prices; suspension of convertibility of the dollar into gold; and a $4.7 billion cut in federal spending.[84]

> James Fletcher, [NASA's new Administrator] by a total mistiming went to see Nixon on the day that the dollar was floated and Nixon said, listen I don't have $12 billion ... do something for half.[85]

The Office of Management and Budget, equally concerned to limit budget requests going to the Congress confirmed the

84 James Reichley, ***Conservatives in an Age of Change*** pp 219-225.

85 Hans Mark, interview with author, September 8, 1995.

reduced sum, as William Lilly, NASA's Chief Budget Officer, recalled.

> When we first sat down with them in the summer to discuss fiscal 1973 they told us that our total budget ... would not go above its present level ($3.3 billion). When we calculated it out, it meant that if the Administration approved the shuttle project, we'd have to live with about a $1 billion peak funding figure.[86]

The two-stage shuttle that top NASA officials had been pushing for the past two years had an estimated peak funding level of over $2 billion.

December 1971 had been earmarked by top NASA officials as the deadline for a presidential decision on the shuttle. Many in NASA were growing concerned about both the costs and psychological effects of a stretch out. Holding the industrial teams together would become problematic if the programme were deferred for another year.

> We were worried as hell that we'd lose the momentum the program had gained, and beyond this we seriously doubted that the ... contractors could, or would continue to pump in their own dollars.[87]

Fletcher also felt that approval for some kind of shuttle had to come in that year if NASA was to remain a leading force in space technology. Once it was clear that the economic climate would not sustain a $12 billion programme, Fletcher instructed the Phase-B contractors to develop alternative design configurations that would cost no more

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86 William Lilly, NASA Chief Budget Officer, quoted in Claude Barfield, 'Intense Debate, Cost Cutting Precede White House Decision to Back Shuttle,' p S16615.

87 Charles Donlan, quoted in ***Ibid.*** p S16615.

than $5 billion to develop.[88] This was no easy task, as North American Rockwell's Shuttle Manager, Bastian Hello reflected:

> We were directed to move over to the other vehicle, and proposal time was hurrying along and we had some catch up work to do. So it became ... intense ... we were given some three months to propose and that became a nightmare.[89]

In addition to the new Phase-B contracts, Fletcher also let out a new contract to Mathematica to study all the alternative designs emanating from the extensions. The first study had been forced upon NASA by the Office of Management and Budget; NASA went into the second voluntarily in the hope that it would justify an economical and practical programme.[90] The key factor in the economic analysis was market demand; the number of flights. Accurate mission models were elusive and scenarios for future flight traffic rates over the 1979-90 time period varied considerably.[91] Indeed forecasting future demand was an impossible task and so was driven by political considerations as much as anything else. It was believed that the agency's 'position would be significantly

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88 The Grumman/Boeing team and Lockheed also received Phase-B extension contracts even though they had not technically participated in Phase-B.

89 Bastian Hello. interview, with author, April 27, 1995.

90 Grey Jerry. ***Enterprise*** pp 78-79.

91 Memorandum from Dale Myers to Deputy Associate Administrator, Planning, June 17, 1971 (NASA History Office Archive, Washing ton DC). Flight rates varied from 492 to 732.

weakened'[92] if Mathematica's economic analysis eliminated the space station. Some models, therefore, included the space station while others simply escalated the commercial demand. The debate over the number of flights persisted for some time before Mathematica eventually settled on a 514 mission model for its study.[93] Controversy, nevertheless, persisted: in particular, traffic models and estimates of operational costs were continually modified and attacked as the programme progressed.

By the end of the summer the Mathematica study had revealed that even if operational costs rose to $10 million per launch all but 5 per cent of the shuttle's planned missions would be cost effective.[94] The configuration favoured by Klaus Heiss, who was leading the Mathematica staff, was a parallel burn Thrust Assisted Orbiter System based on a design first derived at McDonnell Douglas.[95]

> ... WE CONCLUDE THAT THE DEVELOPMENT OF A TAOS [Thrust Assisted Orbiter System] SPACE SHUTTLE SYSTEM IS ECONOMICALLY JUSTIFIED, within a level of space activities between 300 and 360 Shuttle flights in the 1979-1990 period, or about 25 to 30 Space Shuttle flights per year, well within the U.S. Space Program including NASA and DOD.[96]

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92 ***Ibid.***

93 Heiss K.P. Morgenstern O. ***Economic Analysis of the Space Shuttle System: Volume 1.***

94 The two-stage fully-reusable configuration had a projected per-launch cost of $4.6 million.

95 LeRoy Day, letter to the author, May 5, 1996.

96 Heiss K.P. Morgenstern O. ***Economic Analysis of the Space Shuttle System: Volume 1.*** p 1-11. Emphasis in original.

According to Heiss it was difficult to get a hearing late in the summer because:

> everybody in Washington was designing a shuttle. There seemed to be a hundred pet ideas ... and for a while nobody listen to anybody else.[97]

Allied with Robert Lindley, NASA's Director of Engineering and Operations, Heiss pressed McDonnell Douglas and Grumman to include the thrust assisted orbiter system configuration in their presentations to NASA, but 'some NASA officials kept telling them to forget it, the configuration had no chance.'[98] Resistance to the thrust assisted orbiter configuration primarily came from Marshall because it eliminated the need for a future human piloted booster, which Marshall hoped to build.[99]

Heiss's strongest recommendation came in the form of a memo sent to Fletcher on October 28, 1971. In it he stated that the Mathematica studies showed the thrust assisted orbiter to be the economically preferred choice. Among the reasons given for its economic superiority were: lower development costs of less than $6 billion; lower development risks; equal capability with the originally proposed system; elimination of the need for an immediate decision on a reusable booster; and the assurance of an

97 Klaus Heiss, quoted in Claude Barfield Claude 'Intense Debate, Cost Cutting Precede White House Decision to Back Shuttle,' p S11667.

98 *Ibid.*

99 LeRoy Day, letter to the author, May 5, 1996.

early programme definition and thus a purpose to the agency.[100]

Although the final Mathematica report was not due for release until the end of January 1972, the memo gave a clear indication to Fletcher of its conclusions. Armed with this information and under pressure from the Office of Management and Budget, the Office of Science and Technology and the Presidents Scientific Advisory Committee, the Program Office began to push hard for the thrust assisted orbiter configuration.[101]

The debate continued right through November and December, but TAOS eventually emerged as the leading candidate and was presented to President Nixon on January 5, 1972.

> Jim Fletcher and George Low went out to California ... and had a meeting with President Nixon, who was [on vacation] ... and the paper they took and the briefing they gave on shuttle said that we would develop the vehicle for $5.15 billion ... in the purchasing power of the 1971 dollar and that we would do it by September 1979, but that we needed about an 18 month schedule pad on the back of that and a billion dollars of funding over and above that to account for contingencies, but that we would be willing to embark on the 5.15 and the '79 time period as a planned program.[102]

During that 40 minute meeting, Nixon stated that both military and civilian applications should be emphasised if

100 Scott Pace, ***Engineering Design and Political Choice*** p 40.

101 LeRoy Day, letter to the author, May 5, 1996.

102 Robert F. Thompson. interview, with author, September 7, 1995.

the programme was to be accepted. He also appeared to like the idea that 'ordinary people' would be able to fly in the shuttle. Low and Fletcher stressed 'the fact that the shuttle is not a $7 billion toy, that it is indeed useful, and that it is a good investment'.[103] Nixon replied:

> ... that even if it were not a good investment, we would have to do it anyway, because space flight is here to stay. Men are flying in space now and will continue to fly in space, and we'd best be part of it.[104]

The programme was thus accepted by Nixon on the terms set out by Fletcher and Low and on the same day he publicly announced:

> I have decided today that the United States should proceed at once with the development of an entirely new type of space transportation system designed to help transform the space frontier of the 1970s into familiar territory, easily accessible for human endeavour in the 1980s and '90s. ... It will revolutionize transportation into near space, by routinizing it. It will take the astronomical costs out of astronautics. ... The new year 1972 is a year of the conclusion for America's current series of manned flights to the moon. ... they bring us to an important decision point - a point of assessing what our space horizons are ... and of determining where we go from here. ... the space shuttle program is the right next step for America to take, in moving out from our present beach head in the sky to achieve a real working presence in space.[105]

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103 George Low, memorandum for the record, January 12, 1972 (NASA History Office, Washington DC).

104 *Ibid.*

105 Statement by President Richard Nixon, press release from the Office of the White House Press Secretary, January 5, 1972 (National Air and Space Museum Archive, Washington DC).

Nixon also sent a letter to the chairman of his New Hampshire campaign committee on that day announcing his candidacy for reelection.[106]

Unbeknown to NASA, senior White House staff members had started to support a shuttle development programme. Although Nixon's economic policies were slowing down the rate of inflation, unemployment continued to hover around 6 per cent. While much of the domestic bureaucracy was busy implementing the new economic policy, a few technicians at the Office of Management and Budget were assigned to develop statistical models plotting the effect of economic conditions on the outcomes of presidential elections. The study's results, which were reported to George Shultz and John Ehrlichman, not surprisingly showed that rapid economic growth benefited an incumbent president seeking reelection.[107] Nixon did not need statistical models to know that falling unemployment in 1972 would increase his chances of reelection. He thus decided to plunge ahead with increased federal spending to produce boom conditions in the election year.[108] The approval of the shuttle programme may well have been part of that agenda. It is certainly believed that Peter Flanigan, a White House policy level staffer, persuaded Nixon to go ahead with the shuttle

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106 Nixon Richard. ***The Memoirs of Richard Nixon*** p 541.

107 Edward Tufte, ***Political Control of the Economy*** (New Jersey, Princeton University Press, 1978) p 136.

108 James Reichley, ***Conservatives in an Age of Change*** p 226.

because the continuing depression in the aerospace industry and that the relatively high rate of unemployment among the national pool of scientists and engineers would soon become election issues.[109] Whatever Nixon's motivations were, the shuttle's proponents had finally cleared the first hurdle; presidential approval. The shuttle's development could now be programmed into NASA's FY 1973 budget.

Nixon's January 5 decision, to commit $5.15 billion to the development of a partially reusable shuttle initially prompted an adverse response in Congress. As Representative Don Fuqua (Democrat, Florida) recalled, many members of the congressional space committees were perturbed by NASA's conversion to a partially reusable system:

> We had just finished defending one configuration on the Floor and then suddenly they announced they were going to change it. ... We all wanted to know how long they had known they were going to change and how much of this kind of thing was going on behind the committee's back. They explained the reasons behind the changes, and everybody calmed down.[110]

Despite the initial consternation over NASA's "sudden" shift, strong allies quickly mobilized in support of the new configuration against a notably weak opposition. After a morning of government and industry witnesses describing how necessary the shuttle was for America's future, Representative Bella Abzug (Democrat, New York) appeared

109 Francis Hoban, interview with author, May 15, 1995.

110 Don Fuqua, quoted in Ken Hechler, ***Towards the Endless Frontier*** p 289.

before the Manned Space Flight Subcommittee in opposition to the Shuttle, on the afternoon of March 14, 1972.

> Now that NASA has reached the Moon, it is seeking a new, similarly glamorous toy for its next project and it feels that the Space Shuttle would be just the ticket. ... I would remind you that the President recently vetoed as fiscally irresponsible a bill that would provide only $2 billion for child care Centers, a mundane but urgent issue for the millions of working parents in this country.[111]

Defenders of the shuttle adroitly counteracted her argument by portraying the programme as one solution to America's rising unemployment problem. The American Federation of Labour and the Congress of Industrial Organizations (AFL-CIO) executive council supported Nixon's decision to develop the shuttle and urged Congress to defend the programme and its potential 50 000 jobs.[112] Taking up this issue, John Wydler (Republican, New York) neutralized Abzug's case by commenting on the predicament of aerospace workers in their own state:

> Thousands of these people are out of work, thousands of their children are suffering ... They need some relief, some help from Government. It would seem to me we would be helping those people if we were to pass this program. For that reason alone, it would seem a very people-orientated program.[113]

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111 Bella Abzug, quoted in ***Ibid.*** p 290.

112 'AFL-CIO Backs Space Shuttle' ***The Machinist*** (March 2, 1972) p 1.

113 John Wydler quoted in Ken Hechler, ***Towards the Endless Frontier*** p 291.

Wydler was not the only member to attack Abzug. Ken Hechler (Democrat, West Virginia) recollects the how curt a reception Abzug received at the hearings:

> Other committee members gave Mrs Abzug a hazing for daring to oppose and presuming to know more than they did about the worth of the Shuttle. It almost seemed at times that they were attempting to accomplish a rite of exorcism for the heretical beliefs she espoused.[114]

As the debate moved to the Floor the recommendation that NASA should receive the $200 million requested to begin the shuttle development had powerful backing. Representative Les Aspin (Democrat, Wisconsin) was the only member to introduce an amendment to eliminate the $200 million and to have the National Academy of Sciences conduct further studies into the programme. The amendment was soon crushed with both the Majority Leader, Hale Boggs (Democrat, Louisiana) and the Minority Leader, Gerald Ford (Republican, Michigan) standing against it. NASA's authorization bill was thus passed with a comfortable majority: 277-60.[115] Challengers in the Senate found themselves in a similar position. A bipartisan coalition of 61 Senators successfully defeated Walter Mondale's amendment to cut shuttle funding, which only received 21

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114 ***Ibid.*** pp 291-292.

115 ***Ibid.*** pp 292-293; 'Senate Vote Coming on Space Shuttle' ***The Machinist*** (May 4, 1972), p 3; Jeffrey Banks, 'The Space Shuttle,' Linda Cohen, Roger Noll, (ed) ***The Technology Pork Barrel*** (Washington DC, The Brookings Institute, 1991), p 203.

votes.[116] The shuttle plans had thus passed through both houses giving NASA the sanction to proceed.

[116] 'Shuttle Vote Brightens Aerospace Job Outlook' ***The Machinist*** (May 18, 1972), p 1.

Chapter 4

Separation and Specific Definitions

> Technology succeeds by taking the world apart and putting it back together in productive ways. ... In the operation of technical systems the components must, at the outset, be separated and precisely defined.[1]

Conditions of Invention.

While the titanic struggles over the definition of the entire shuttle system were enacted, below the surface rippled the process of sub-system definition. Due to the complex nature of the shuttle, there was a great deal of interaction between the NASA Centers and the shuttle contractors through the years 1968 to 1975. Changes in design of the entire system imposed changes in design at the sub-system level; and activity at the sub-system level shaped the range of possibilities of the entire system. One central motivation behind many of these changes was to ensure that the programme adhered to the tight budget limitations, as Bastian Hello, North American Rockwell's Shuttle Program Manager, told *Aviation Week and Space Technology* at the time:

> The system design decisions we're making are reflecting costs in two areas, overall program

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1 Langdon Winner, ***Autonomous Technology: Technics-out-of-Control as a Theme in Political Thought*** (Cambridge, Massachuetts, MIT Press, Eighth Printing, 1992), p 182.

costs as well as costs per flight, and we're hitting both of those very, very hard.[2]

However, minimizing overall system complexity and gross lift-off weight also formed a large part of the agenda for change.[3] Fluidity of design, both at the level of the sub-system and at the level of the entire system, therefore, dominated this period (see figure 4:1 for changes to shuttle configuration).

Within this chapter I explore the process of separation and precise definition of some of the shuttle's main components. A detailed analysis of every sub-system is not possible within the boundaries of this particular thesis, so I have focused on some key examples required to carry out the shuttle's major functions: namely, ascent to orbit, on-orbit manoeuvrability, reentry, return flight and atmospheric flight.

Subverting Gravity.

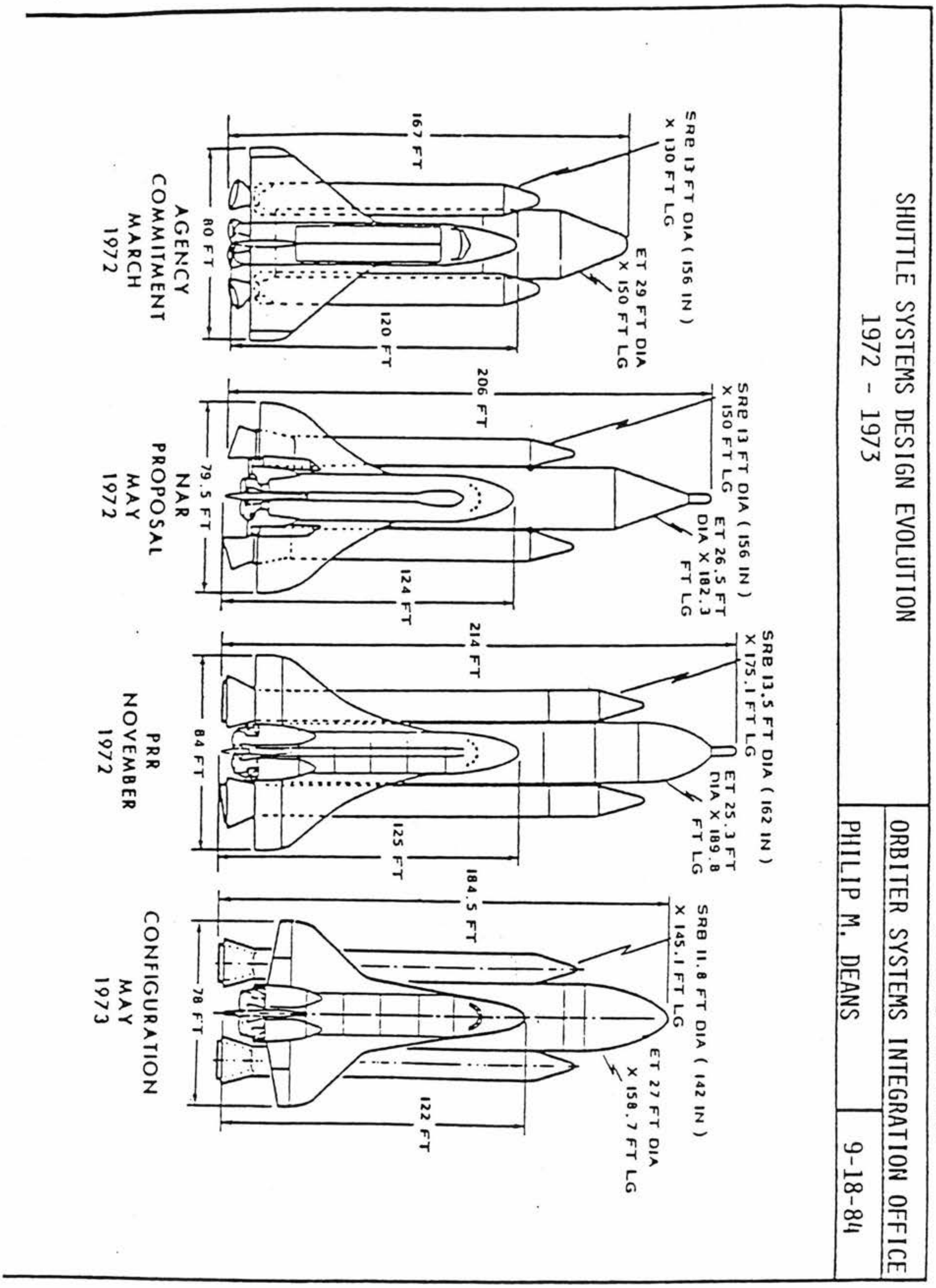
Ascent to orbit ranges of between 100 to 800 nautical miles with launch azimuths from 28.5^0 to 90^0 inclinations were defined as the primary functions of the shuttle's main propulsion system.[4] Entwined with these basic functions

2 D. Fink, 'Shuttle Subcontractor Briefings Begin,' ***Aviation Week and Space Technology*** (November 27, 1972), p 48.

3 Bastian Hello, interview with the author, April 27, 1995; 'Space Shuttle Design Changes Cut Costs' ***Aviation Week and Space Technology*** (November 13, 1973), pp 18-19.

4 ***Space Shuttle Program Requirements Document: Level 1***, July 1, 1970 (NASA History Office Archive, Washington DC); ***Space Shuttle Program Requirements Document: Level 1, Change No.2***, December 3, 1970 (NASA History Office Archive, Washington DC).

Figure 4:1.-



Source: NASA History Office Archive, Washington DC.

were the additional requirements of reusability and low operational costs. Each presented technological problems and, as engine design moved through its conceptual phases, each was tied to multifarious technological solutions.

Function, along with operational environment, are important factors in engine design. Knowledge of the Earth's gravitational pull and its effects on orbital dynamics play a pivotal role in shaping the technological systems required for propulsion. The velocities required to overcome the effects of the Earths gravitational pull are enormous. For the orbiter to reach NASA's reference parking orbit, 100 nautical miles circular, the vehicle had to achieve speeds of over 17 000 miles per hour.[5] This physical problem did however, have technological solutions. Two principal innovations, the rocket engine and high energy rocket fuel, had matured sufficiently by 1957, for the Soviet Union to launch Sputnik I. The number of successful launches after this event multiplied rapidly. Between 1957 and 1972 over 1 200 launches into orbit occurred world-wide, with the most dominant activities

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5 The force of gravity acts on all bodies in an identical manner, giving any unsupported mass at a given distance from the centre of the Earth, the same acceleration towards the Earth. To escape the Earth's gravitational pull, acceleration to a velocity of 36 700 feet per second (7 miles/sec, or 25 200 mph) is required. Lower velocities are required for orbital insertion, which are dependent on the characteristic of the orbital plane required, ie. circular or elliptical and the altitude of the orbit. Lyn Dutton, David de Garis, Richard Harding, ***Military Space*** (London, Brassey's UK, 1990), pp 31-32; Bernard Lovell, ***The Origins and International Economics of Space Exploration*** (Edinburgh, University Press Edinburgh, 1973), pp 1-4; Arthur C. Clarke, ***The Exploration of Space*** (London, Temple Press Ltd, 1951), p 31; Jerry Grey, ***Enterprise*** p 94.

centred in the Soviet Union and the United States.[6] At the outset of the shuttle programme, therefore, the US space community had accumulated a significant amount of knowledge and experience in the methods, practices and associated technologies needed to manipulate the Earth's gravitational pull to propel an artificial object into orbit. Many of the basic technologies surrounding the shuttle's propulsion system had thus already been established.

Cryogenic fuels, which had played vital roles in NASA's crusade to the Moon, is one example. Higher performance cryogenic rocket fuel technology followed on into the shuttle.[7] On the Saturn V Moon rocket, liquid oxygen and kerosene fuelled the five F-1 rocket engines at the bottom of the stack. But the six J-2 engines, five on the second stage and one on the third, were fuelled with liquid oxygen and liquid hydrogen.[8] The two upper stages employed cryogenic fuels, liquid oxygen/liquid hydrogen (LOX/LH2), because these technologies provided higher specific impulse figures than had been achieved

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6 Total world wide launches, including the US military, up to 1972 amounted to 1218. Out of this total NASA launched 267. Bernard Lovell, ***Ibid.*** pp 1-3, 28-33; Linda Neuman Ezell, ***NASA Historical Data Book, Volume II*** p 26: Linda Neuman Ezell, ***NASA Historical Data Book, Volume III*** p 21; Joseph Green, Harriet Brown, ***A Summary of Major NASA Launches: October 1, 1958 - December 31, 1989*** (Florida, KSC Historical Report No.1, June 1992).

7 ***Ibid;*** John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 2.*** (Houston Texas, NASA, JSC, Conference Publication 2342, 1985), pp 600-617; Armis Worlund, John Jamieson, Timothy Cole, Tibor Lak, 'Cryogenic Propellant Management: Integration of Design, Performance and Operational Requirements,' Norman Chaffee. (ed) ***Space Shuttle Technical Conference, Part 2.*** (Houston Texas, NASA, JSC, Conference Publication 2342, 1985), pp 585-599.

8 J. Mitchell, (ed) ***Thirty-Five Years in Power for America: A History of the Rocketdyne Division of Rockwell International*** (Rocketdyne Publications Services, n.d).

previously.[9] During the late 1960s innovation planning in rocket engine technology at NASA was directed towards improvements in utilizing cryogenic fuels, as the Director of the Chemical Propulsion Division at NASA's Office of Advanced Research and Technologies, Adelbert Tischler, recalled:[10]

> At the time there was no clear definition of the next generation of space vehicle. I was satisfied, however, that the F-1 was a good enough booster engine and that the bigger need was for improved upper stage engines. ... Also with considerable experience in using LOX/LH2 I had no fear of going in that direction even though many "experts" at the time were adverse to using LH2 in particular.[11]

A continuation along this technological path for the shuttle's main engines was, for many, the 'logical choice.'[12]

> The hydrogen/oxygen technology for rocket propulsion was pretty mature at that time and that was pretty well accepted as a method of propulsion.[13]

> ... one of the most dramatic advances in the whole business was the use of hydrogen. ... its just the most efficient fuel that we have right now, short of nuclear.[14]

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9 Specific impulse is defined as the thrust produced per unit of mass of propellant per second.

10 Despite the low bulk density disadvantage of the liquid oxygen/hydrogen combination, the performance advantage of hydrogen over kerosene (RP-1) is roughly 50 per cent greater on an equivalent mass basis. That advantage is huge when large velocity increments must be produced by a stage. Adelbert Tischler, letter to the author, 13 November 1996.

11 Adelbert Tischler, letter to the author, November 13, 1996.

12 Robert Thompson, ***Von Karman Lecture*** p 5.

13 Robert Thompson, interview with the author, September 7, 1995.

14 Robert Freitag, interview with the author, June 5, 1995.

At the outset of 1970 the estimated gross lift off weight of NASA's original two-stage shuttle was 3.5 million pounds. This translated into a total engine cluster of thirteen 400 000 pound thrust liquid oxygen\liquid hydrogen engines; ten on the booster and three on the orbiter.[15] Simplification of operational and turnaround logistics encouraged the employment of the same engine configuration on both the orbiter and booster, but not everybody within NASA agreed with this arrangement. For example, a leading spacecraft designer at Johnson, Max Faget, recalled:

> [There was an] agenda to use the same engines on both the first stage and the second stage; well, that was wrong.[16]

Dissenters at Johnson, led by Max Faget, were pushing the Office of Manned Space Flight to employ a liquid oxygen/kerosene (RP-1) engine similar to the F-1 for the booster. Faget agreed that the orbiter 'had to have a hydrogen engine because it needed a high specific impulse,' but thrust per cubic foot, because of the cost/size relationship, was thought far more important on the booster than increases in specific impulse.[17] This debate continued for sometime, but events ultimately rendered it superfluous once the human piloted booster was dropped. Instead, it

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15 ***Space Shuttle Program Requirements Document: Level 1,*** July 1, 1970 (NASA History Office Archive, Washington DC); W. Normyle, 'NASA Asks Quick Shuttle Replies' ***Aviation Week and Space Technology*** (February 23, 1970), pp 16-17.

16 Max Faget, interview with the author, September 9, 1995.

17 Max Faget, interview with the author, September 9, 1995.

took on a different form in the discourse surrounding the choice between liquid or solid propellant booster systems, covered later in this chapter.

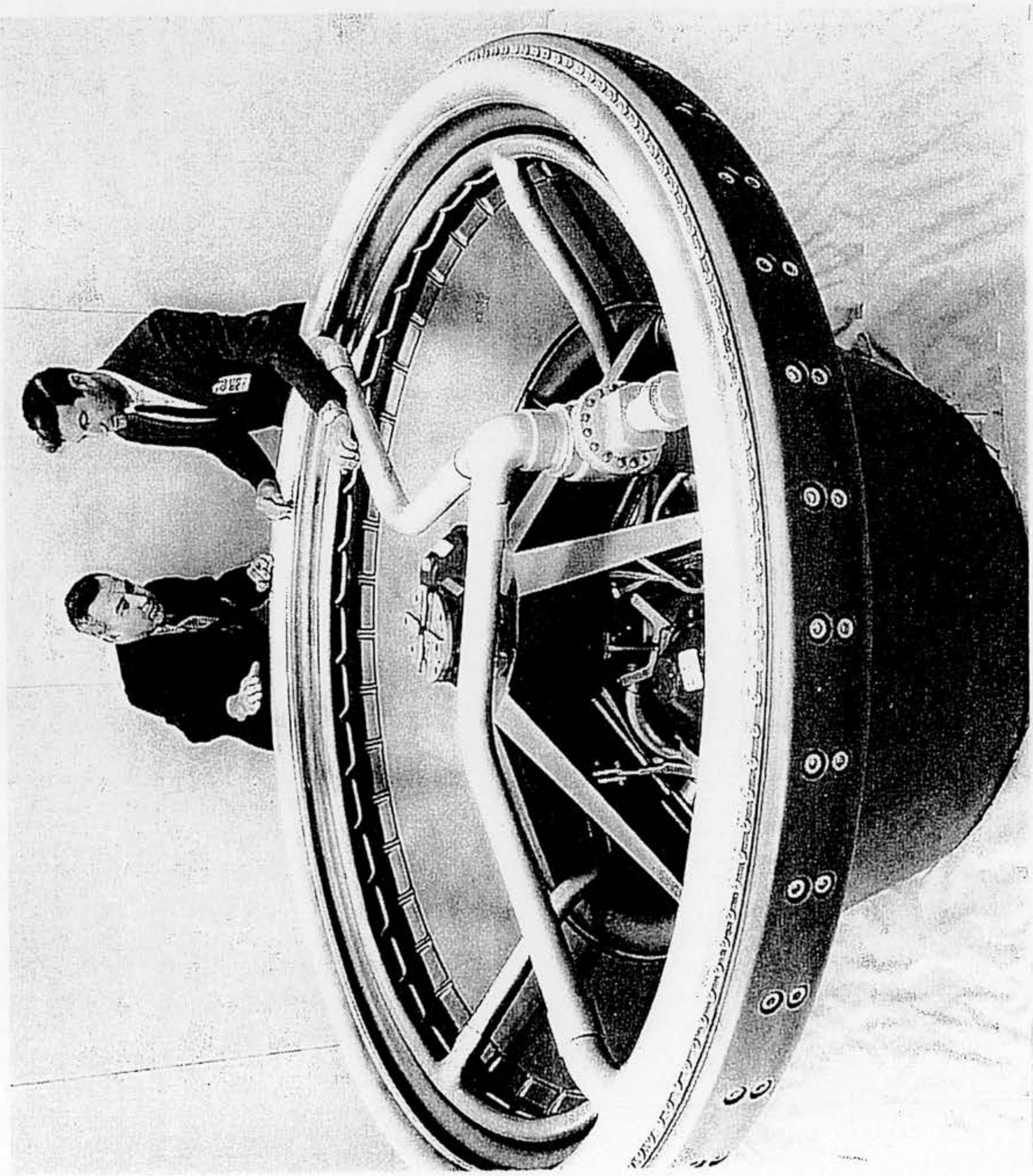
Three development paths for a liquid oxygen/hydrogen engine were open to NASA at the start of the shuttle programme: one, embark upon the development of a new aerospike engine concept; two, continue with the traditional J-2 type gas generator combustion cycle engine design, improving its performance and reducing both its size and mass/thrust ratio; or three, embark upon the development of new staged combustion cycle engine concept.

Aerospike, originally proposed by a General Electric engineer, was a Rocketdyne development that had arisen from a joint NASA/Air Force project in the mid to late 1960s (see Print 4:1). A significant step forward in rocket engine technology, it offered many advantages, such as: less mass than a conventional engine; and, because of it unique nozzle design, less aerodynamic drag at the base of the rocket or spaceplane.[18] Thus, aerospike's major innovation was in nozzle design, which was designed to solve the problem of varying expansion ratios from sea level to altitude. Otherwise, as Rocketdyne engineer, Lee Solid, recalled it was basically a J-2 engine:

> We had taken J-2 running gear, J-2 pumps, J-2 valves, J-2 start system, just about everything on a J-2 except the thrust chamber and built what

18 Lee Solid, interview with the author, July 26, 1995; NASA, ***Technological Influence on the Space Shuttle Development*** (Texas, Lyndon B. Johnson Space Center, June 8, 1986) p 5-12.

Print 4:1



Courtesy of Rocketdyne.

> we called a linear engine, which was an aerospike [engine].[19]

Aerospike's nozzle engine differed from the traditional bell nozzle engine in that high pressure supersonic exhaust flow from the combustion chamber would be directed obliquely inward to expand on the central body. Expansion outward would be limited aerodynamically to the Prandtl-Meyer expansion angle, which is defined by the ambient (atmospheric) external pressure. The exhaust stream area leaving the base of an aerospike engine could thus be confined to produce maximum force at very low back pressure; with lesser exhaust stream area and thrust force when higher back pressure existed. The exhaust stream area would thus have been self-adjusting and, therefore, at near maximum thrust coefficients for all back pressures. Since the centre body was small, much of the mass of a bell nozzle could be eliminated.[20] Rocketdyne had built and tested the hardware during the late 1960s, but many at NASA were sceptical of its utilization on the shuttle. Two main problems troubled NASA engineers:

> [Aerospike] looked like an interesting concept. ... The trouble was that ... this meant that you tied the type of rocket to the configuration and in the early stages when we were ready to begin development on the engine we hadn't decided yet exactly what the orbiter was going to look like and this would have tied these two developments

19 Lee Solid, interview with the author, July 26, 1995.

20 Adlebert Tischler, letter to the author, June 16, 1997; Lee Soild, interview with the author, July 26, 1995.

> together, which is always a dangerous thing to do.[21]

And;

> The NASA decided that the aerospike technology just wasn't there yet ... The problem we had with the aerospike ... was that we were really struggling with how to cool it. We just didn't have enough cooling surface to cool it.[22]

So finally the programme administrators decided not to go that route, but to specify a standard bell type engine, which was relatively universal and could be bolted onto a variety of airframe configurations (see figure 4:2).[23] With its proposal rejected, Rocketdyne had to put together a bell nozzle engine configuration very quickly.[24]

This left the competition between a high pressure, staged combustion cycle engine and a traditional gas generator cycle engine; both bell nozzle configurations. The staged combustion cycle engine was basically an aircraft cycle engine concept transferred to rocket technology. All of the propellants used to spin the turbines were to be used again in the combustion chamber. As a result very high pump pressures were required; around 3000 pounds per square inch in the combustion chamber and approximately 6000 pounds per square inch discharge pressures at the pump. In contrast, the gas generator cycle

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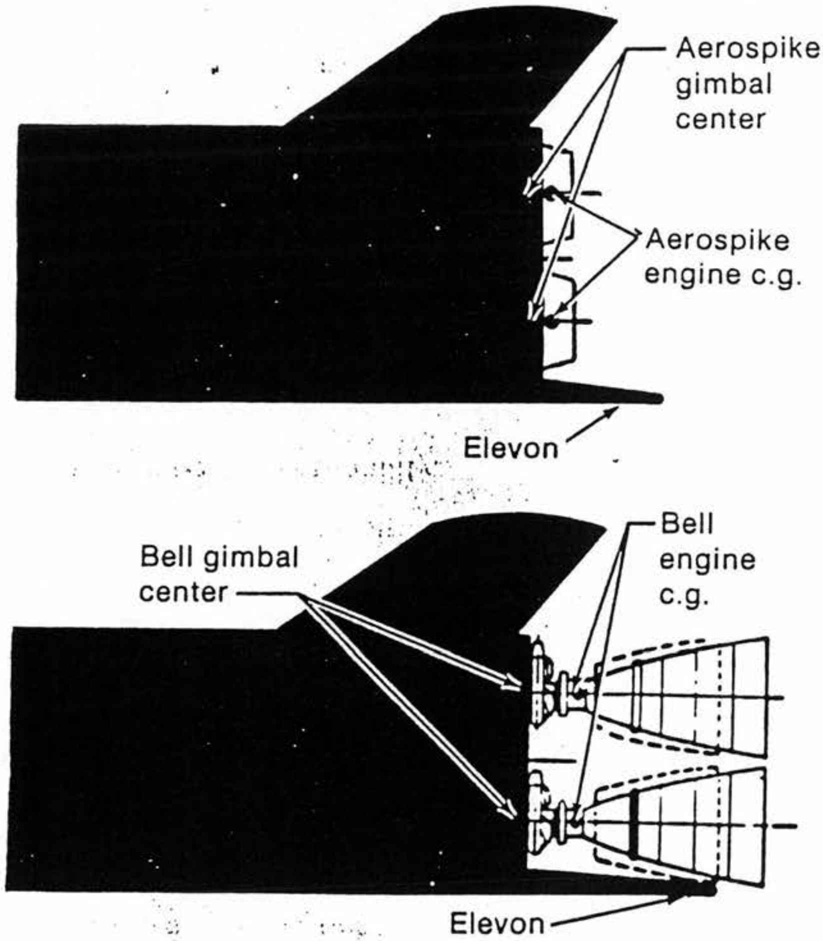
21 LeRoy Day, interview with the author, June 29, 1995.

22 Lee Solid, interview with the author, July 26, 1995.

23 LeRoy Day, interview with the author, June 29, 1995.

24 Lee Solid, interview with the author, July 26, 1995.

Figure 4:2.



- Comparison of Aerospike and bell engine installations.

Source: NASA. ***Technology Influences on the Space Shuttle Development*** p 5-13.

engine exhausted whatever propellant that was used to combust and drive the turbines. Consequently the design was less efficient, but it operated with much lower pump pressure requirements (see figure 4:3).[25]

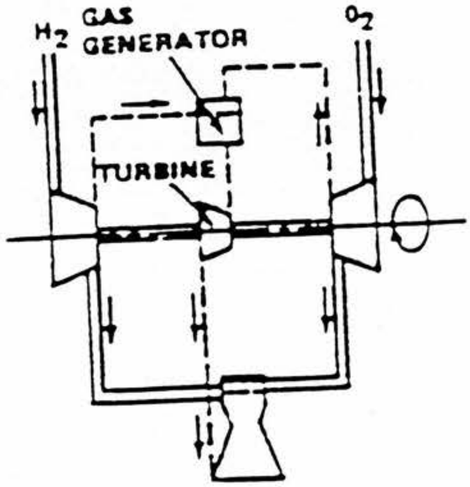
Knowledge about staged combustion cycle engine technology had been accumulated on a joint NASA\Air Force low level funding programme during the 1960s. Managed by the Air Force Rocket Propulsion Laboratory programme, Pratt & Whitney, the principal contractor, had produced a liquid oxygen/liquid hydrogen, high-pressure engine designed to generate high specific impulse figures, but was roughly half the size of a conventional low pressure liquid oxygen/liquid hydrogen engine. The programme, which had no specific mission, was originally scheduled to end in 1972, but on August 18, 1970 the Air Force terminated its support and let NASA take it over.[26] Although the shuttle's main engines were judged to need at least twice the amount of thrust of Pratt and Whitney's, it was a technology that some in NASA thought could be expanded.[27] Gas generator engines, such Rocketdyne's J-2, had, on the other hand, already been fully developed and utilized in NASA launch vehicles. Consequently some members at Johnson began to put

25 Lee Solid, interview with the author, July 26, 1995; Max Faget, interview with the author, September 9, 1995; Adelbert Tischler, interview with the author, May 3, 1995.

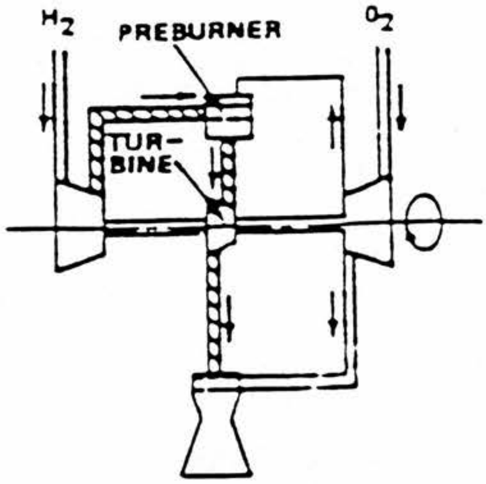
26 Michael Yaffee, 'Reusable Rocket Motor Unveiled' ***Aviation Week and Space Technology*** (August 31, 1970), p 38.

27 LeRoy Day, interview with the author, June 29, 1995.

Figure 4:3.



GAS GENERATOR



PREBURNER

Source: John McCarty. Byron Wood. 'Space Shuttle Main Engine: Interactive Design Challenges' p 606.

pressure on the Office of Manned Space Flight to continue along this technological path.

The Marshall Space Center, however, favoured proceeding with the development of a new staged combustion cycle engine for the shuttle. Higher specific impulse and increased efficiency were, for Marshall, determining requirements for a low operational cost, reusable system. Accord was not, however, uniform among all members of NASA. The same dissenters at Johnson that had questioned the Office of Manned Space Flight over a booster engine configuration, also raised an objection to Marshall's rationale to develop a new staged combustion cycle engine. Gambling higher specific impulse, at higher pump pressures, against "proven" technology was thought by Faget's rebels imprudent. The staged combustion cycle was considered by these engineers to be overly complex and they foresaw problems with cooling within the pre-combustion chamber and at the turbopumps.[28] Their position was that the gas generator cycle engine was known to perform well and would have a significant weight advantage over the staged combustion cycle. The gas generator cycle engine was also claimed to be a better design because the pumps and turbines, driven by a separate gas generator, could be decoupled for testing purposes from the development of the injector and thrust chamber. The only area of technology in

28 Max Faget, interview with the author, September 9, 1995.

which the gas generator cycle engine was regarded by Faget's rebels to be at a disadvantage was cooling the thrust chamber at pressures as high as 4000 psi.[29] As such, they proposed that a modified version of the gas generator cycle engine could be constructed that would meet shuttle specifications (see table 4:1 for engine specification comparisons).

Engine design however, was under the management of Marshall and it rejected the gas generator engine. As Max Faget recalled wryly:

> The people at Marshall had fallen in love with this [staged combustion] cycle ... and although we had lobbied hard against this decision we didn't have a very good chance because they knew more about engines.[30]

Marshall's engineers argued that a modified gas generator cycle engine had some inherent characteristics, namely chamber cooling, chamber operations at higher mixture ratio and turbine efficiencies, that cast serious doubt on the promise of substantially lower engine weight at only a slightly reduced specific impulse. Even assuming an optimistic break-even position on weight versus specific impulse, both Marshall and the Office of Advanced Research and Technology (OART) argued that a higher specific impulse engine translated into a heavier payload lifting

29 NASA, ***Technology Influence on the Space Shuttle Development*** p 5-14.

30 Max Faget, interview with the author, September 9, 1995.

Table 4:1.

Shuttle Main Engine Comparison.

	Gas Generator.	Staged-Combustion.
Chamber Pressure, psi.	4000	3000
Pump discharge pressure, psi.	5293/4703	6288/5904
Envelope. -Diameter (OD), in. -Length, in. -Area ratio.	 128 242 220	 128 242 157
Thrust (vacuum), lb.	474 200	475 800
Specific impulse (vacuum), seconds.	455.0	461.1
Chamber cooling. -Heat flux (at throat). -Coolant flow rates.	 90 20.8	 72.5 26.0
Engine accessories weight. -Dry, lb. -Wet, lb.	 4952 5606	 6240 6640

Source: Adapted from table 5-1. NASA, ***Technology Influence on the Space Shuttle Development*** p 5-17.

capability.[31] Adelbert Tischler, director of the Chemical Propulsion Division at OART and Director of Shuttle Technologies for both the Office of Manned Space Flight and OART, estimated that even a 1 per cent degradation in specific impulse would reduced payload capacity by about 10 000 pounds.[32]

On October 12, 1970, Associate Administrator for Manned Space Flight, Dale Myers, concurred with Marshall's position. Due to limited funds for the shuttle programme Myers instructed that NASA's efforts should concentrate on the high pressure, staged combustion cycle engine, so he terminated activities related to the gas generator cycle design.[33] Compared with the gas generator cycle engine, the higher specific impulse and thrust-to-weight ratios of the staged combustion engine proved an attractive proposition to the Office of Manned Space Flight when considering the overall size that the engine had to be.[34]

As the engine programme advanced towards fabrication, both Marshall and the main engine contractor, Rocketdyne had to reconcile the complexity of design with

31 NASA, ***Technology Influence on the Space Shuttle Development*** p 5-16.

32 William Normyle, 'Shuttle Poses Dominant Challenge' ***Aviation Week and Space Technology*** (June 22, 1970), p 115.

33 NASA, ***Technology Influence on the Space Shuttle Development*** p 5-16.

34 Robert Thompson, ***Von Karman Lecture*** p 5.

specifications that were atypical in the realms of rocket engine technology. NASA's general specifications for the shuttle's main engines were:

* 400 000 pounds thrust at sea level with continuous throttling down to 50 000 pounds thrust with nozzle extended.
* Minimum specific impulse of 455 seconds.
* Thrust vector control of +/- 7 degrees.
* Multiple restart requirements and a maximum time between restarts of 30 days in orbit.
* Continuous run ranging from 10 to 600 seconds.
* Durability of 100 re-uses, 500 starts and 10 hours between overhauls.[35]

The most distinctive of these requirements was reusability. Few rocket engines had been designed for reuse. Almost all previous engine hardware had been fabricated for expendable vehicles and thus, only required an operational life of a few hundred seconds. The shuttle, envisaged as a reusable means to access orbit, was expected to conduct up to 100 missions before major refurbishment. Accordingly, engine design had to incorporate a much longer lifespan than had previously been required, as Rocketdyne engineer, Lee Solid commented:

> In the past we designed engines to be used once or twice, ... but we never designed a system that we would reuse over and over again. Whether we were designing it for tactical systems or defense systems, or whether we were designing it for space application, it was always a one time use thing. Now we had to think some new disciplines. We had to think maintainability and reliability and life. I [was] going to have to design and develop life into these things.[36]

35 William Normyle, 'Shuttle Poses Dominant Challenge' ***Aviation Week and Space Technology*** (June 22, 1970) p 115.

36 Lee Solid, interview with the author, July 26, 1995.

Notwithstanding these differences, reuse was not entirely new to NASA's rocket engineers. Testing requirements for previous engines demanded an element of reusability to keep development costs reasonable. The F-1, for example, was run up to 35 times between take down and inspection.[37] Nonetheless, the extent to which the shuttle's engines were planned to be reused went far beyond what NASA and its contractors had accomplished before. Many of the problems to be faced would thus be unique.[38] Rocketdyne and Marshall, therefore, had to embrace a new approach to engine fabrication. A crucial part of that new approach involved the use of line replaceable units. Major engine components were designed so that they could be interchangeable without system re-calibration and individually removed or installed either in the field or at the factory.[39]

Along with specifications on performance and hardware life, Marshall and Rocketdyne also had to contend with constraints on engine dimension and mass. The reusable nature of the shuttle contributed to a relatively high growth trend in hardware mass. As most of the vehicle was designed to return to Earth, it contained many systems that

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37 Adelbert Tischler, letter to the author, June 16, 1997.

38 Lee Solid, interview with the author, July 26, 1995.

39 Robert Ryan, Larry Salter, George Young, Paul Munafo, 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402; John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 600-617.

would remain inactive during the ascent to orbit. These technologies, such as the orbiter's undercarriage, essentially represented surplus payload until they were activated.[40] In addition, the reentry, flight and landing characteristics also place a priority on the relationships between engine weight, engine thrust and engine size. Situated at the tail end of the orbiter, the three engine cluster had to produce sufficient thrust to lift the vehicle to a characteristic orbit, yet be light so as not to induce critical repercussions on the orbiter's centre of gravity on the journey back down; and be small enough so that it would fit within the relatively small, as compared to Apollo, space at the back of the orbiter.[41]

Compliance with many of these specifications was, to a large extent, an inherent part of the engine's design. The engineering solution to higher specific impulse and augmentation of thrust-to-weight was to increase combustion pressure. An increase in combustion pressure, demanded an increase in power to feed the propellants to the combustion chamber. The central issue thus facing both NASA and Rocketdyne, was the development of turbo-machinery that would provide sufficient horsepower to meet performance demands. Turbo-machinery efficiency, turbine flow rate, turbine temperatures and mechanical dynamics all stood as

40 Max Faget, interview with the author, September 9, 1995.

41 Lee Solid, interview with the author, July 26, 1995; Max Faget, interview with the author, September 9, 1995; Robert Lindstrom, interview with the author, August 17, 1995.

constraints on potential power levels. The predictions of operating regimes, temperatures, pressures, rotary speeds and combustion processes, were all unprecedented.[42] As Marshall engineer, Bill Sneed recalled:

> I remember a fellow by the name of Thompson that was one of the leading engineers on the SSME [space shuttle main engine]. I remember in all of his projections he showed speeds and temperatures that were just almost off the chart in comparison to things that we had developed up to that time.[43]

The goal of greater combustion pressure had to be accomplished through improvements in component technology. A crucial factor in engine fabrication was, therefore, the requirement for exotic materials that could be formed into high strength yet light components.[44]

An early interruption to the stabilization of engine design descended from the universal drive to control the mass of the entire shuttle system. As engine component development advanced, the mass of each component spiralled upwards, generating a concern over the growth in total engine mass. Engineers at Marshall and Rocketdyne were thus mandated by upper management to initiate strategies in

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42 Lee Solid, interview with the author, July 26, 1995; Robert Ryan, Larry Salter, George Young, Paul Munafo, 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402; John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 600-617.

43 Bill Sneed, interview with the author, August 21, 1995.

44 Lee Solid, interview with the author, July 26, 1995; Robert Ryan, Larry Salter, George Young, Paul Munafo, 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402; John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 600-617.

weight reduction. Attention quickly focused on structural design. In many areas where engine components would have been assembled using conventional bolts and flanges, Marshall and Rocketdyne made a tactical shift to welded constructions. This change in approach allowed the engine builders to comply with short-term mass restrictions, but resulted in long-term difficulties. Most of the engine's components were formed in extremely complex shapes and required a considerable amount of time and care in bonding the materials together (see figure 4:4).

By the end of 1974 weld development was still a major area of concern and project focus. Testing, which was scheduled to begin in 1974, suffered major delays as process development for critical welds, on both the turbo-machinery and combustion devices, elevated to the status of "pacing item": a technology that determines the overall schedule of a systems development.[45] David Winterhalter, chief of NASA's shuttle propulsion branch, commented at the time:

> We are doing a lot of learning on the welding of the first one or two components that come down the line. We're also vulnerable to a component problem in that we don't always have another piece of hardware right behind, necessarily, if we lose a test component.[46]

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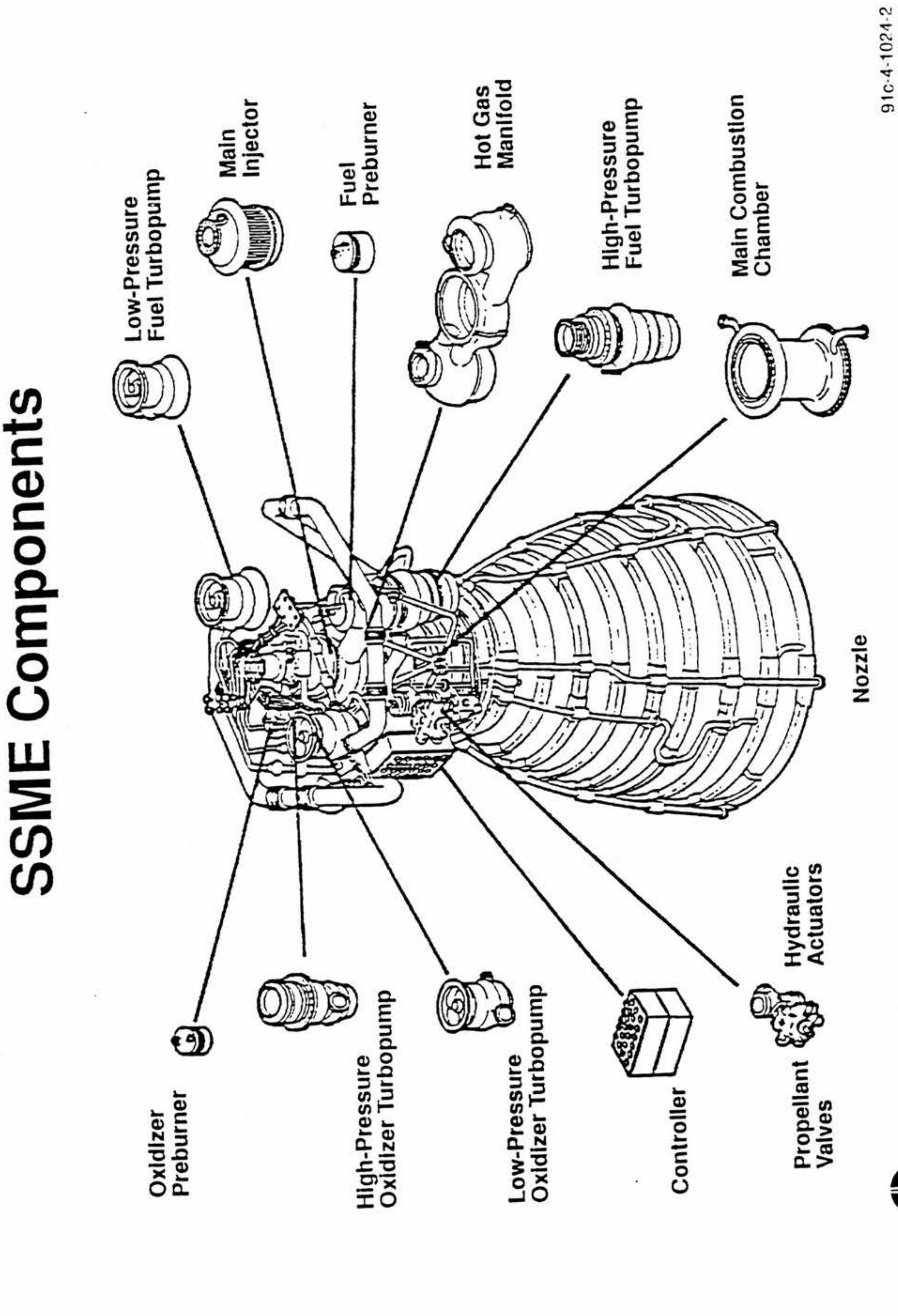
45 ***Ibid;*** Robert Lindstrom, interview with the author, August 17, 1995; Marshall Space Flight Center, Rockwell International, 'Summary of Space Shuttle Main Engine Review,' ***Space Shuttle 1975 Status,*** report for the Committee on Science and Technology, US House of Representative (Washington DC, US Government Printing Office, February 1975), pp 39-41, 91-93; Craig Covault, 'Shuttle Engine Passes Critical Milestone,' ***Aviation Week and Space Technology*** (June 30, 1975), pp 37-42.

46 David Winterhalter, quoted in, Craig Covault, 'Shuttle Engine Passes Critical Milestone,' ***Aviation Week and Space Technology*** (June 30, 1975), p 37.

Figure 4:4.

Source: NASA History Office Archive.



Fuel Supply.

As highlighted above, the removal of the orbiter's internal fuel tanks represented the most significant deviation from NASA's original shuttle design. Simplification of design was the main impetus behind the introduction of the external tank. The complexity of building and operating an orbiter with internal fuel tanks had aroused a lot of concern within NASA as Johnson's Director, Christopher Kraft recalled:

> The structure was driven by our lack of confidence in being able to build a tank that could be an internal part of the aeroplane structure, because you had to be able to test it structurally after every flight ... and there was no way you could guarantee you weren't going to blow the aeroplane up by testing it. ... That's what drove the tank out of the machine ... I don't think structurally we could have done otherwise.[47]

By incorporating both the liquid hydrogen and the liquid oxygen fuel tanks to a single external structure, the complexity of systems integration was reduced and the development costs of the orbiter were significantly lowered (see figures 4:5 and 4:6). In addition, the approach relieved pressure on the tight restrictions in the mass growth of the orbiter and the uncertainties involved in achieving optimum performance from the main engines.[48]

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47 Christopher Kraft, interview with the author, September 1, 1995.

48 J.P. Loftus, S.M. Andrich, M.G. Goodhart, R.C. Kennedy, 'The Evolution of the Space Shuttle Design,' unpublished presentation paper presented to the Production and Development Panel of the Presidential Commission on the Space Shuttle Accident, March 6, 1986 (NASA History Office Archive, Washington DC), p 6.

Figure 4:5.
Source: W.H. Morita, (ed) ***Space Shuttle System Summary*** (Rockwell International, Space Systems Group, SSV80-1, May 1980).

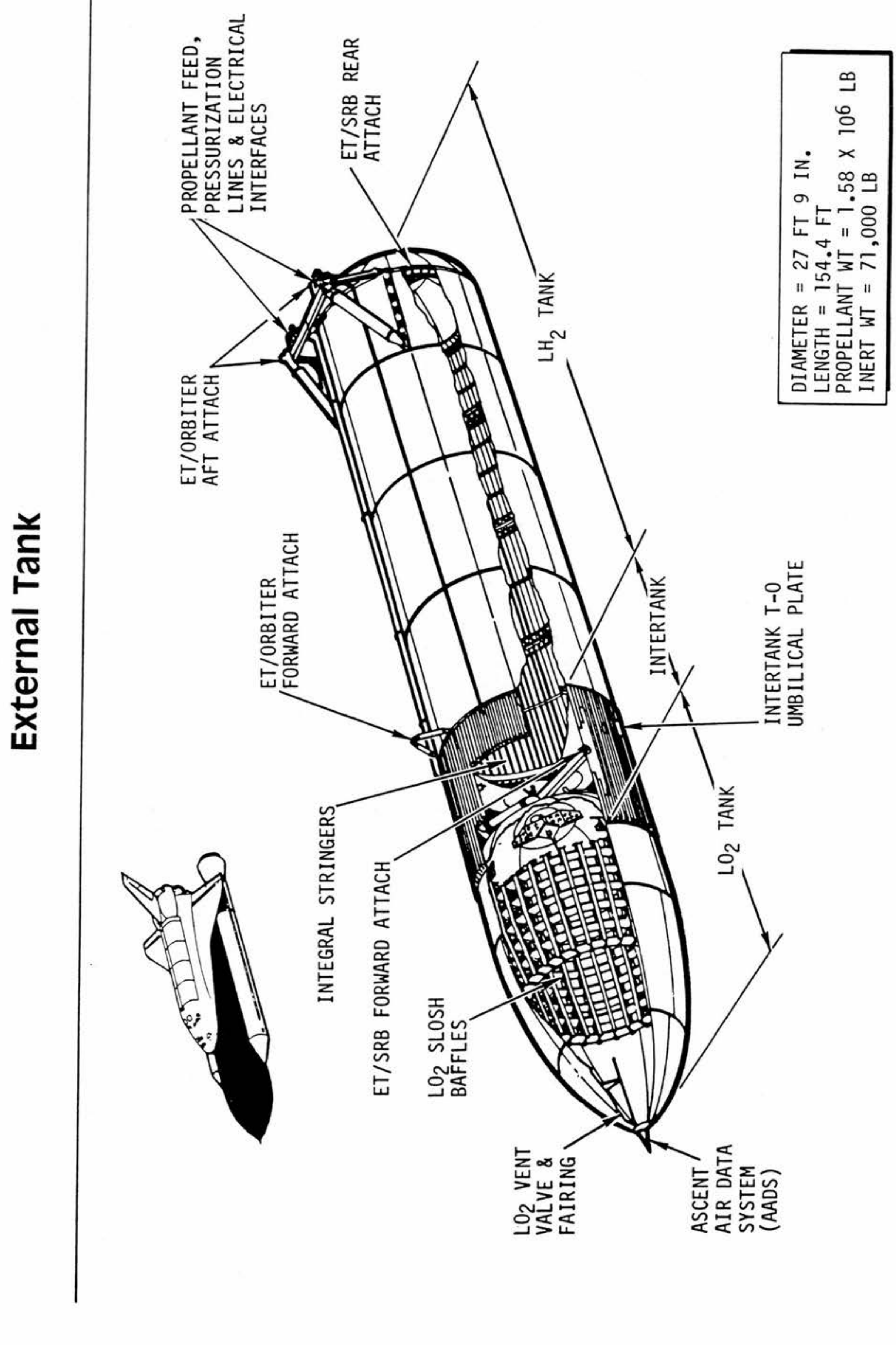
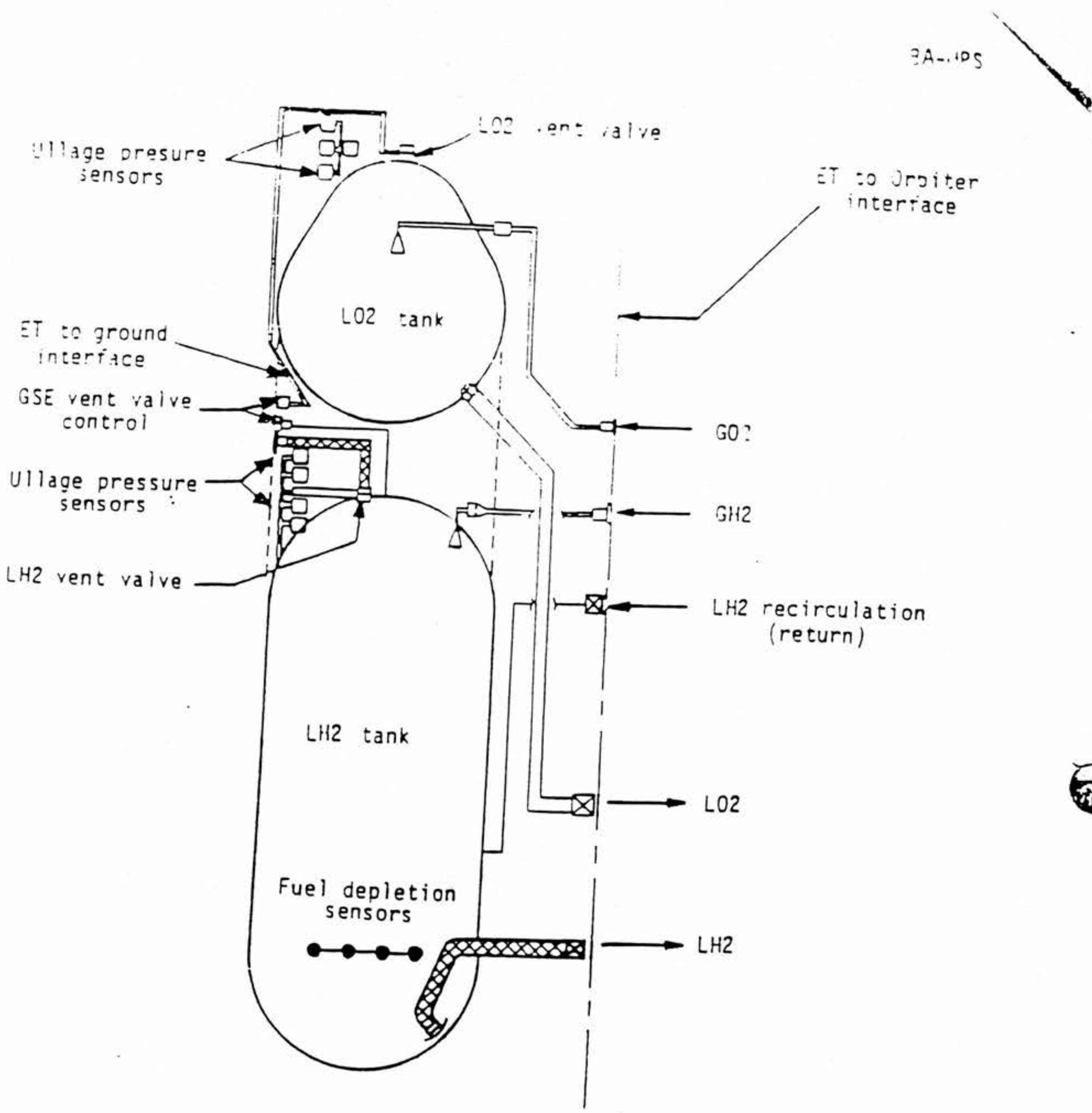


Figure 4:5.

Source: NASA History Office Archive.



· External tank schematic.

The primary function of the external tank, namely to house the liquid oxygen and liquid hydrogen that would fuel the orbiter's three main engines, was the basic determinant of its overall size. The amount of fuel the system would be required to carry was dictated by both the thrust output and operation time of the orbiter's three main engines. A thrust specification of 400 000 pounds for each engine translated into a combined consumption rate of over 64 900 gallons of liquid propellant per minute. Since NASA had selected a parallel burn stacking arrangement, the main engines, ignited before lift-off, would have to propel the shuttle virtually all the way to orbit: a duration of about eight minutes. The external fuel tank, thus had to be sized to contain over 520 000 gallons of liquid propellant.[49]

Another critical design parameter shaping the external tank was its mass ratio. As the external structure had to go virtually all the way to orbit, it had to withstand all the aerodynamic forces, vibrations and speeds (around 27 000 feet per second) of the flight. In addition, because mass is of vital importance in travel to orbit, every pound of tank was equivalent to every pound of payload. Hence, NASA's tank designers had to keep the mass fraction of the tank as high as they could get it: the tank had to be very light, yet structurally very sound. The result was a unique

49 Dennis Jenkins, ***Space Shuttle*** pp 225-226; W.H. Morita, (ed) ***Space Shuttle System Summary*** p 28.

tank design that comprised a very thin aluminum wall.[50] Just the welding of aluminium alone was, in 1971, a 'very difficult thing to do,'[51] but coupled with the size of the tank walls, each weld would typically have to land:

> Anywhere from about 1/4 to 3/8 of an inch [on the liquid oxygen tank], whereas in the liquid hydrogen tank a lot of the metal is only about a 1/10 of an inch thick.[52]

Although distinct in its requirements, the design of external tank drew heavily on NASA's past experience with the tanks in the Saturn rockets (see figure 4:7).

> In concept [the external tank] ... was from the Saturn V, but it was designed differently because its shape was different. It was not as big in diameter ... it used less pieces to make a circle. ... The bulk heads were different shapes ... The technologies however, were the same.[53]

The Saturn tanks were several feet in diameter larger, so NASA had learnt a lot about welding capabilities. Nevertheless, in each tank there was going to be almost a mile and a half of weld:

> So every weld had to be perfect because if any one of them starts leaking, it doesn't have to rupture, just leak, then you can ... lose a vehicle.[54]

Welding was thus going to be a very crucial part of production process.

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50 James Odem, interview with the author, August 21, 1995.

51 James Kingsbury, interview with the author, August 16, 1995.

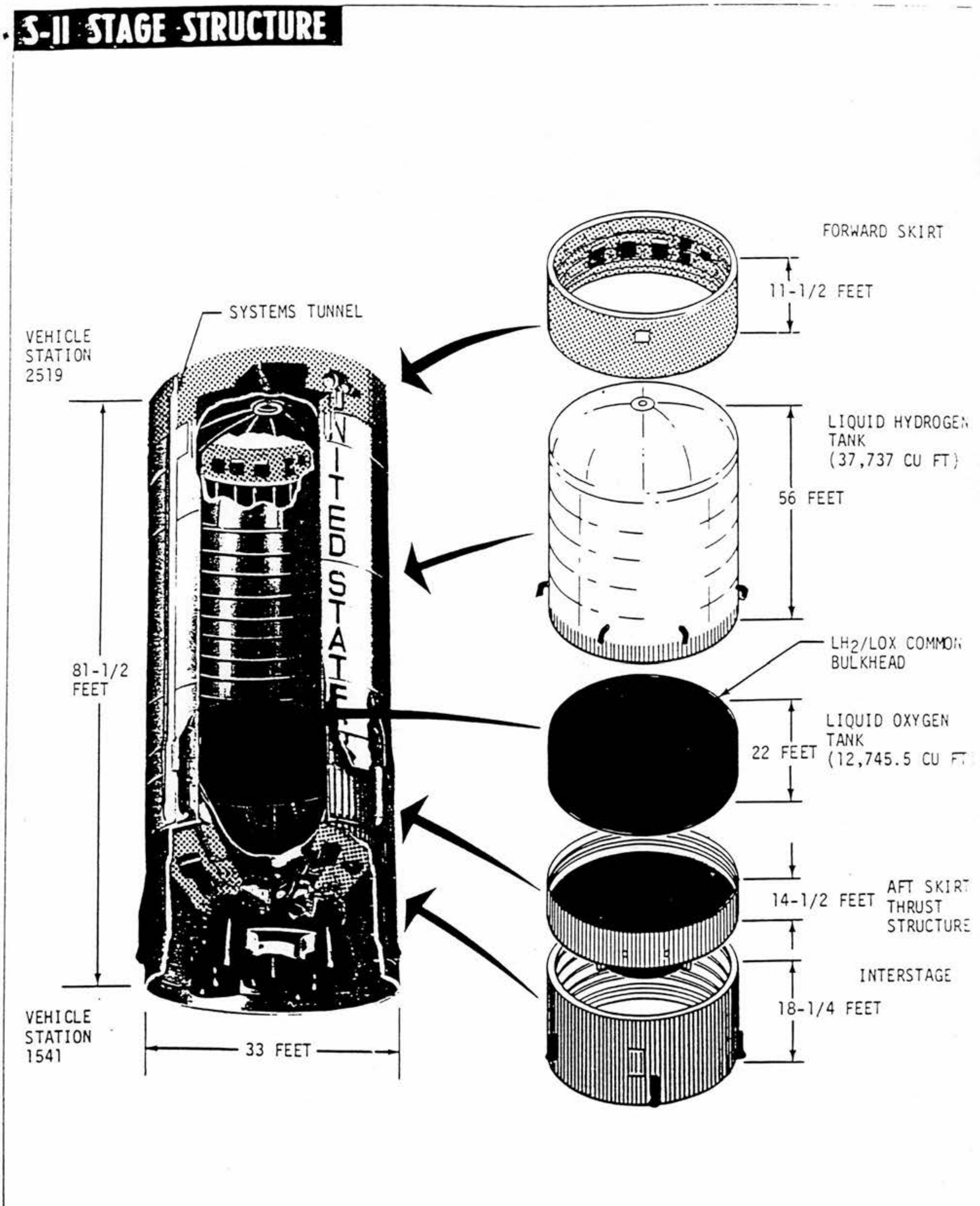
52 James Odem, interview with the author, August 21, 1995.

53 James Kingsbury, interview with the author, August 16, 1995.

54 James Odem, interview with the author, August 21, 1995.

Figure 4:7.

Source: Kennedy Space Center Archive.



Predictions of aerodynamic forces on ascent were one of the first factors to modify areas of the external tank's design. Late in 1972 the external tank's original cone-shaped nose was changed to an ogive shape as early aerodynamic studies indicated that this shape would give a better performance. Throughout 1973, overall length of the external tank was gradually decreased and its diameter increased as the aerodynamic characteristics and interference effects of the integrated vehicle were better understood.[55]

> To be able to fly a vehicle stable you want to have the center of pressure in front of the center of gravity. So what we had to do was balance the diameter and the size to where basically the center of gravity was countered near to what we call the intertank, that bolts the [liquid oxygen and liquid hydrogen tanks] together, because that was about where the combination of the whole vehicle center of gravity would be. We wanted the center of pressure to be a few feet ahead of that; that way, as long as those two are separate, then your control laws are a lot simpler.[56]

At the end of 1973 negotiations and further refinements to an external tank design tapered off. A configuration acceptable to NASA was established in early 1974 and with the design process at satisfactory a point of closure hardware development began.

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55 James Odem, interview with the author, August 21, 1995; 'Shuttle Weight Cut 20 Percent Over Last Year,' ***Defense/Space Business Daily*** (March 1, 1974), p 5; Charlie Dill, J.C. Young, B.B. Roberts, M.K. Craig, J.T. Hamilton, W.W. Boyle, 'The Space Shuttle Ascent Vehicle Aerodynamic Challenges: Configuration, Design and Data Base Development,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** pp 151-152.

56 James Odem, interview with the author, August 21, 1995.

Ballistic Solutions.

Although Nixon had given his approval of the thrust assisted, parallel burn orbiter system, the specific details on booster technology had not been established in early 1972.

> When we first got the go-ahead for the program ... we were still not clear whether we were going to use liquid boosters ... or solid rockets and that was a major controversy in the early part of the program.[57]

The choices surrounding booster technology at the outset of 1972 were: development of a new liquid fuelled pressure-fed system or modification of a solid propellant rocket.[58] Grumman Aerospace and Boeing Corporation were also promoting the traditional series-burn, pump-fed liquid system.[59]

Recovery versus expendable, coupled with development versus operational costs, hinged the debate between liquid fuelled and solid fuelled booster technology. Initial thinking within NASA had centred around reusable liquid systems fashioned for recovery after a sea ditch. This would keep operational costs low because the rockets would

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57 LeRoy Day, interview with the author, June 29, 1995.

58 William Hieronymus, 'Three Shuttle Booster Concept Studied,' ***Aviation Week and Space Technology*** (January 10, 1972), pp 46-48; 'Shuttle Decision Hailed as NASA Victory,' ***Aviation Week and Space Technology*** (January 10, 1972), pp 15-16; Zack Strickland, 'Pressure-Fed Booster Explore,' ***Aviation Week and Space Technology*** (January 24, 1972), pp 40-41.

59 The Grumman\Boeing concept was based on a modified Boeing S-1C, which they claimed could be developed for about half the cost of a liquid pressure-fed system and would entail less technological risk. They also cited an advantage of less weight over the pressure-fed system, 300 000 pounds as compared to 1 million pounds, because it would not need thick walls to withstand tank pressurization. Despite the obvious benefits associated with thrust to weight specifications, reduction in weight was considered less of a risk because there was great uncertainty at the time as to what would happen to a million pound pressure-fed booster on water impact. Michael Yaffee, 'Alternate Booster Evaluation Set,' ***Aviation Week and Space Technology*** (January 24, 1972), pp 36-37.

be reused, but development costs would be high, because they were complex boosters to fabricate. Expendable solid fuelled booster systems were also examined, because as relatively simple vehicles they would keep development costs low. However, throwing them away after each launch vastly increased operational costs.[60] Liquid fuelled rocket technology had been the mainstay of NASA's experience in human space flight. For many, both within NASA and the aerospace industry, it appeared a given that NASA would use liquid propellants for the shuttle's booster system.

> The solid rocket people didn't understand why they were still being asked to study this and study that because we had never used solid rockets on a manned program as a major propulsion element. ... they came to me ... and said you are kind of stringing us along, we could be doing some other things here. We just can't understand why you are having us carry on these studies because we don't believe NASA can be serious about using solid rockets. ... They asked von Braun's opinion, he told them he felt sure that NASA, when they settled down, they would make the decision to go with the liquid booster. ... So the contractors were a little perplexed as to why we were still pushing that way.[61]

The liquid booster technologies though, were presenting a number of problems for NASA's engineers.

> The initial approach was to use liquids ... stay with what we know. However, a group came into the picture which said I think we can recover these [solid] boosters and reuse them. It [was proving] pretty difficult with the liquids. Once you get those engines soaked in sea water the probability

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60 William Hieronymus, 'Three Shuttle Booster Concept Studied,' ***Aviation Week and Space Technology*** (January 10, 1972), pp 46-48; 'Shuttle Decision Hailed as NASA Victory' ***Aviation Week and Space Technology*** (January 10, 1972), pp 15-16; Zack Strickland, 'Pressure-Fed Booster Explore,' ***Aviation Week and Space Technology*** (January 24, 1972), pp 40-41.

61 LeRoy Day. interview with the author, June 29, 1995.

> of using them over is pretty remote, but the solid, which doesn't have a lot of complex mechanisms or machinery, has a chance. And so Thiokol and a couple of other solid people worked on it ... and when they went out and began demonstrating and throwing the thing into salt water and pulling it out and trying to reuse it, it became pretty convincing.[62]

External political pressures also influenced NASA's booster technology decision. Although the Office of Management and Budget had agreed not to become directly involved in any technical judgment after Nixon's announcement, their power over NASA's budget commitments was an effectual leverage on the agency's technological decision making. Office of Management and Budget Director, George Shultz told NASA Administrator James Fletcher, early in 1972:

> With these very real funding constraints in mind, I believe that NASA would be well advised to select a shuttle system which minimizes the risk of cost overruns and allows flexibility to absorb possible cost increases within overall funding constraints. Otherwise, a cost overrun on the shuttle could lead to an undesirable stretch-out of the operational date for the shuttle or serious cutbacks in other productive NASA programs which, in turn, could jeopardize the shuttle program.[63]

In addition, NASA was being forced to act quickly on a final configuration commitment. The House Committee on Science and Astronautics had 'demanded a firm decision' on NASA's choice of booster and shuttle configuration by the

62 Robert Freitag, interview with the author, June 5, 1995.

63 Letter from George Shultz, Director of the OMB to James Fletcher, February 16, 1972 (NASA History Office Archive, Washington DC).

time they appear before the committee on March 16, 1972,[64] which especially concerned William Lilly, NASA's Comptroller:

> In reviewing the approach to the shuttle cost analysis ... we [have] become a bit apprehensive that some considerations that appear vital to a well rationalized decision on the shuttle configuration may not be adequately treated in the time frame which has been established for the final study effort.'[65]

In connection with the booster technologies Lilly felt that it was important to expose 'the degree of uncertainty associated with pressure-fed development costs versus solid development costs,' given the tight budget and lack of flexibility for contingencies.[66]

Early in March, NASA Administrator James Fletcher came to the conclusion that the 'use of solid boosters in the parallel staged configuration represents the optimum choice from combined technical and budgetary points of view:'[67]

> The decision concerning liquid or solid boosters was a difficult one. It involves a trade-off between future benefits ... and earlier savings ... liquid boosters have lower potential operating costs, while solid boosters have lower development cost. The decision concerns development risk which is lower for the solids because the technical unknowns are less, and also risks in operational costs which favor the solids because the economic exposure of failing to

64 Letter from James Fletcher to Casper Weinberger, Deputy Director, OMB, March 6, 1972 (NASA History Office Archive, Washington DC).

65 Letter from William Lilly to Dale Myers, February 11, 1972 (NASA History Office Archive, Washington DC).

66 *Ibid.*

67 Letter from James Fletcher to Casper Weinberger, Deputy Director, OMB, March 6, 1972 (NASA History Office Archive, Washington DC).

> recover a booster is much less. Another approach to reaching this decision involved adding all costs together - development, investment and operating. However the conclusions here are heavily dependent on the mission model, with the liquid booster favored if we assume a large number of flights per year, and the solids if the number of flights per year is less. Based on the results of our contractor studies and our in-house estimates, and with our great concern about holding down development costs in these years of tight fiscal constraint, our decision must be in favor of the solid booster.[68]

A meeting between George Low and Donald Rice, of the Office of Management and Budget on March 7, confirmed that NASA was going to go ahead with the development of the solid rocket boosters for the shuttle.[69] In announcing the decision Fletcher said the development costs would be reduced by $350 million and that the decision was based on lower development costs at less technical risk.[70]

On-orbit Manoeuvres.

If the shuttle was going to retrieve or repair satellites in orbit, rendezvous and dock with orbiting hardware and serve as a supply vehicle for a possible future space station, then a technological system that would enable the orbiter to manoeuvre in orbit, turn on its axis and provide on-orbit stability, had to be an integral part of the

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68 *Ibid.*

69 George Low, memorandum for the record, meeting with Don Rice, March 8, 1972 (NASA History Office Archive, Washington DC).

70 Zack Strickland, 'Single Shuttle Contractor Planned' ***Aviation Week and Space Technology*** (March 20, 1972), pp 14-15.

system. Manoeuvring and attitude control systems were thus important to both NASA and the Air Force.[71]

The absence of air in space means that the orbiter's aerodynamic control surfaces (its wings, tail, flaps, elevons, etc.) have no value. A complex of many small rocket engines, collectively known as the reaction control sub-system (RCS), would thus have to be positioned on the orbiter to enable the vehicle to move around its own centre of gravity; that is to change its pitch, yaw and roll (see figure 4:8).[72] This system alone, however, would not be able to provide sufficient thrust to perform orbit circularization, orbit transfer, or de-orbit, so a secondary rocket engine system, an orbital maneuvering sub-system (OMS), would also be necessary.

Knowledge about the physics and technological requirements of on-orbit manoeuvres had been accrued on both Gemini and Apollo. On the Apollo lunar and command module's the OMS and RCS engines were configured to use a hypergolic propellant combination (nitrogen tetroxide/Aerozine-50). Hypergolic propellants are extremely toxic and very corrosive. When brought together they ignite spontaneously, which serves well inside the combustion chamber of a rocket engine, but can be very dangerous if accidentally spilt. Special safety precautions

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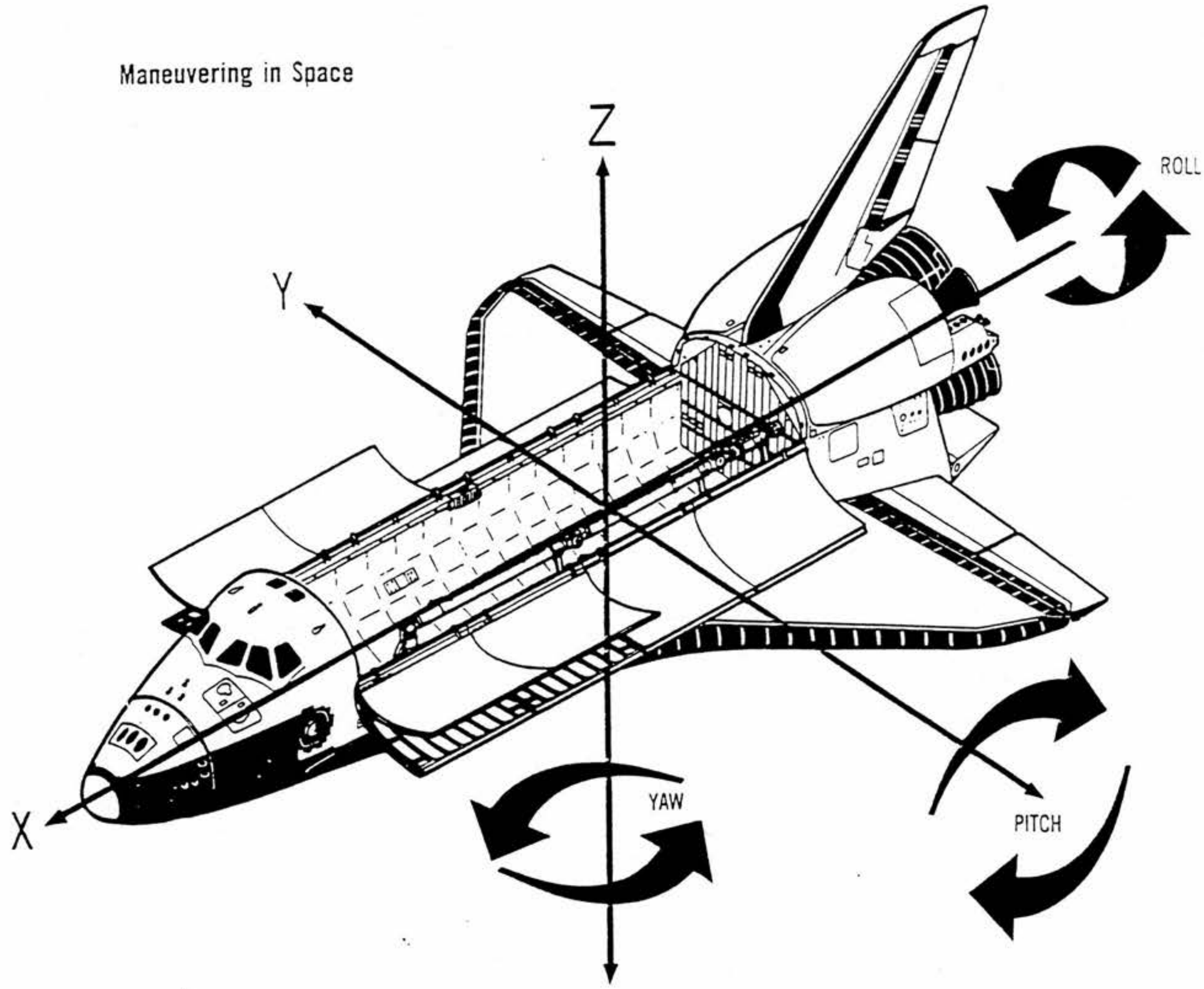
71 William Normyle, 'Shuttle Poses dominant Challenge' ***Aviation Week and Space Technology*** (June 22, 1970), p 120.

72 Jerry Grey, ***Enterprise*** pp 95-96.

Figure 4:8.



Source: NASA History Office Archive.

are thus imperative when working with this technology. Consequently, a continuation with hypergolic propellants for the shuttle was thought to be imprudent as it could impede a perceived frequent turnaround process. Simplification of logistics, operation and maintenance, combined with rapid turnaround requirements, prompted NASA engineers to move away from hypergolic's and design orbital maneuvering and reaction control systems using a hydrogen/oxygen propellent combination, as a chemical engineer, Norman Chaffee, recalled:[73]

> So our going in position was that we really needed to be working with hydrogen oxygen propulsion ... systems and that persisted in our planning for two or three years.[74]

Apart from being relatively safer than hypergolics, a hydrogen\oxygen system promised higher specific impulse figures and, because the design would enable both the OMS and RCS internal propellant tanks to be integrated into one structure, a volumetrically more efficient system.[75]

In 1970/71 Johnson took on an extensive technology program in conjunction with Marshall and the Lewis Space Center to examine on-orbit propulsion systems. With demands

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73 Norman Chaffee, interview with the author, September 6, 1995; C. Gibson. C Humphries. 'Orbital Maneuvering System Design Evolution' Norman Chaffee. (ed) ***Space Shuttle Technical Conference, Part 2.*** (Houston Texas, NASA, JSC, Conference Publication 2342, 1985), pp 639-655; Ralph Taeuber. W. Karakulko. D. Blevins. C. Hohmann. J. Henderson. 'Design Evolution of the Orbiter Reaction Control Subsystem' Norman Chaffee. (ed) ***Space Shuttle Technical Conference, Part 2.*** (Houston Texas, NASA, JSC, Conference Publication 2342, 1985), pp 656-672; Frank Anderson. ***Orders of Magnitude: A History of NACA and NASA 1915-1980*** (Washington DC, NASA Scientific and Technical Information Branch, SP-4403, 1981), pp 47-53.

74 Norman Chaffee interview with the author, September 6, 1995.

75 Norman Chaffee. interview with the author, September 6, 1995; C. Gibson. C. Humphries. 'Orbital Maneuvering System Design Evolution,' pp 639-640; Ralph Taeuber. etal. 'Design Evolution of the Orbiter Reaction Control Subsystem,' p 656.

ranging from brief pulsing to relatively sustained thrust for orbit translation or de-orbit, a gaseous supply of hydrogen\oxygen was thought preferable to liquid. This choice, however, gave rise to issues of production and storage of gaseous hydrogen\oxygen and ignition techniques, because hydrogen and oxygen gases do not ignite on contact. Multiple restarts, longer lifetimes, higher cycles, fast responses and reusability also dominated the technical the agenda.[76] Embedded within the cooperative programme, though, was a strong element of competition, as Norman Chaffee remembered:

> At that time, roles and missions were not well defined. This was a NASA activity and each Center was starting to carve out its niche of the business ... the Lewis guys, they wanted hydrogen oxygen propulsion, but the Marshall people wanted to do the on-orbit propulsion and they realized they would probably have to do the attitude control propulsion because of the integrated nature of the thing. We had done the Apollo attitude control and ... although it was a hypergolic system we felt like that was our expertise.[77]

As the design work progressed it became apparent that a hydrogen/oxygen system would be extremely complicated to operate. This complexity generated concerns about reliability and systems integration within the orbiter. In addition, the internal volume constraints and questions of system mass had became more explicit as the size of the

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76 Norman Chaffee, interview with the author, September 6, 1995; William Normyle, 'Shuttle Poses Dominant Challenge,' ***Aviation Week and Space Technology*** (June 22, 1971), p 120.

77 Norman Chaffee, interview with the author, September 6, 1995.

orbiter was slowly reduced during 1971.[78] As the year drew to a close it was also clear that the on-orbit propulsion systems could not escape the rigors of the economic climate.

> When the rubber really hit the road ... the bottom line came out and said we've only got money to do something that we know how to do and have done before. That technology was the hypergolic technology, ... so we ended up the attitude control system went that way [and] ... the on-orbit propulsion system went that way. ... I believe that we could have brought in a good hydrogen oxygen system, which would of had a better record on maintainability, would have been less onerous in its maintenance, ... but its up-front development cost would have been very high.[79]

As the issue of development costs superseded the appetite for advanced technology, ideas on utilizing established technologies burgeoned. Early studies had focused on using the Apollo Lunar Module ascent or descent engine for the OMS. Resurrected in 1971, both engines were seriously examined afresh as viable hypergolic alternatives to a hydrogen/oxygen system. NASA engineers had learnt a lot from Apollo, especially from their mistakes. Nevertheless, requirements for the shuttle's operational environment were very different. To achieve the reliability and operational economy commensurate with the shuttle's requirements, an operating life of hundreds of thousands of

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78 Sufficient internal volume for a low density hydrogen/oxygen system was a significant penalty in a smaller orbiter. Higher density storable propellants, which could produce the specified delta velocity increments and be stored within smaller tanks, thus appeared more attractive. C. Gibson, C Humphries, 'Orbital Maneuvering System Design Evolution,' p 641; Ralph Taeuber, W. Karakulko, D. Blevins, C. Hohmann, J. Henderson, 'Design Evolution of the Orbiter Reaction Control Subsystem,' p 656.

79 Norman Chaffee, interview with the author, September 6, 1995.

thrust cycles with nearly zero maintenance was necessary.[80] Problems with reducing the mass of both the Lunar Module ascent and decent engines, and the high cost of redesigning them for reusability, were issues that eventually persuaded NASA's engineers to abandon the idea and opt for the development of a new, reusable hypergolic OMS engine.[81]

As an overall shuttle configuration advanced towards an initial closure point, the requirements for both the OMS and RCS became more defined. On the smaller, partially reusable, thrust assisted orbiter, the OMS had evolved into a third stage engine. After main engine burn-out and external fuel tank jettison, the OMS engines would have to generate the additional velocity of 90 feet per second to insert the orbiter into the Office of Manned Space Flight's reference mission orbit (delivery of 65 000 pounds to a circular orbit of 100 nautical miles). Once in orbit, a six day mission would require the OMS to fire 12 times to produce 4.5 feet per second velocity increments, so that the orbiter could maintain its orbit. Orbital manoeuvres, rendezvous and satellite retrieval, translated into a delta velocity range of between 32 feet per second and 1500 feet per second for the OMS, and 120 feet per second to 150 feet per second for the RCS. A crossrange capability of 1500 nautical miles, provided by the orbiters delta wings,

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80 Norman Chaffee, interview with the author, September 6, 1995; Wernher von Braun, 'The Reusable Space Transport,' ***American Scientist*** (November\December 1972), p 737.

81 C. Gibson, C Humphries, 'Orbital Maneuvering System Design Evolution,' pp 641-643.

eliminated the need for the OMS to perform positional changes in orbit to line up with the landing target, but a velocity burn of 250 feet per second against the direction of orbit, would be required to slow the orbiter down enough for it to leave space and return to Earth.[82]

Such a multiplicity of functions gave rise to questions over the preferable choice of propellant or propellant combinations for both the OMS and the RCS. Originally nitrogen tetroxide/Aerozine-50, as used on Apollo, was the hypergolic propellant combination choice for the OMS with a mono-propellant, hydrazine, for the RCS. Mono-propellants were, however, also being put forward for the OMS as NASA engineer, Norman Chaffee recalled:

> As we got down to the final choices there was a very strong school that wanted to even drop back away from the hypergolic bi-propellant propulsion systems to go to a mono-propellant hydrazine systems, which had their impetus way back there in Second World War Germany.[83]

Considerations of development risk, cost, safety, maintainability, hardware life, reliability, performance and mass along with an engine design that was regeneratively cooled, pushed NASA towards a bi-propellant

82 ***Ibid.*** pp 645-646; ***Space Shuttle Program Requirements Document Level 1: Revision No. 4.*** (NASA History Office Archive, Washington DC) pp 3, 4-5.

83 Norman Chaffee, interview with the author, September 6, 1995.

system using nitrogen tetroxide, monomethyl hydrazine for the OMS.[84]

> When push came to shove it was a hard trade to make, but the performance of the bi-propellant system ... was just so much better than the mono-propellant system.[85]

A mono-propellant system for the RCS remained until late 1972, but as performance became a more important factor and the potential for integrating the RCS with OMS looked favourable, the trade-off eventually swung over to using nitrogen tetroxide, monomethyl hydrazine on the RCS as well.[86]

Heated Debates.

One shuttle observer noted in 1970 that:

> If there is any clear cut lack of agreement among those planning the space shuttle, it is in the area of thermal protection.[87]

The problem of shielding the orbiter's primary structure from the intense heat induced by atmospheric drag on reentry attracted such visible controversy because its solution was inextricably bound with the design of other major elements of the shuttle. Airframe configuration,

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84 Norman Chaffee, interview with the author, September 6, 1995; C. Gibson, C Humphries, 'Orbital Maneuvering System Design Evolution,' pp 645-646; Ralph Taeuber, etal, 'Design Evolution of the Orbiter Reaction Control Subsystem,' p 656.

85 Norman Chaffee, interview with the author, September 6, 1995.

86 Ralph Taeuber, etal, 'Design Evolution of the Orbiter Reaction Control Subsystem,' pp 656-657.

87 William Normyle, 'Shuttle Poses Dominant Challenge,' ***Aviation Week and Space Technology*** (June 22, 1970), p 99.

structure and materials could not be divorced from the selection of materials and structure of the thermal protection system. Equally, weight and distribution of a thermal protection system could threaten the preservation of design thrust levels of the propulsion system and thus adversely effect payload lifting capability.

Early in 1970 NASA and its contractors focused their attention on four principal thermal protection design concepts: (i) replaceable ablator panels; (ii) metallic heat shields; (iii) nonmetallic materials; and (iv) carbon-carbon hot structures.[88]

Ablator technologies had been developed and utilized on the Mercury, Gemini and Apollo programmes. Essentially an ablator heat shield was a sacrificial outer layer that would burn up on reentry. The concept employed materials that had almost no ability to transfer heat, but would turn white hot, char and then melt away without transmitting energy into the primary structure.[89] Although the development of a low density ablator system for shuttle application was judged as uncomplicated and workable, it was not regarded as feasible unless some of the design requirements imposed were relaxed.[90]

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88 Robert Freitag, interview with the author, June 5, 1995; Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference*** p 1062.

89 Mike Gray, ***Angle of Attack*** pp 212-215.

90 Hans Mark, interview with the author, September 8, 1995; Letter from Hans Mark to Roy Jackson, February 15, 1972 (NASA History Office Archive, Washington DC).

An expensive and complicated refit of the orbiter's thermal protection system after every flight was not in harmony with the discourse on economic and routine access to space. The Office of Manned Space Flight's requirement that the shuttle system perform routinely over 100 missions with a cost-effective level of refurbishment and maintenance, placed a heavy demand on the design of a thermal protection system.[91] Materials that could meet such a specification existed only as fledgling development programmes or research projects.

The inter-related nature of the thermal protection system traverse a much greater distance than its influence on other subsystems. Indeed, the problems and solutions associated with thermal protection were integral to the overall justification of the programme.[92] If a solution could not be found, then the shuttle programme was in grave danger of no longer be able to rationalize itself. Nevertheless, NASA continued its research into ablator techniques in case a backup would be required.[93]

Repeatedly withstanding the thermal environments of reentry was the key determinant of a thermal protection system design. Coupled with this were other induced

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91 ***Space Shuttle Program Requirements Document: Level 1.*** (NASA History Office Archive, Washington DC), p 4.

92 ***Ibid***; David Baker, 'Evolution of the Space Shuttle,' ***Spaceflight*** (September, 1976), p 311.

93 'Shuttle May Use Low-Cost Ablatives,' ***Aviation Week and Space Technology*** (October 5, 1970), p 56.

environments within which the system had to perform; such as acoustic loads, structural deflections induced by aerodynamic loads, the extreme heat and radiation of the sun, the extreme cold of space, and the natural environments on Earth, such as salt, fog, wind and rain; and because the thermal protection system was to cover the exterior of the vehicle, it also had to provide an acceptable aerodynamic surface.[94]

Due to the inter-related nature of the thermal protection system, most of the contractors exhibited a tendency towards combinations of metallic materials in their Phase-B proposals.[95] Design emphasis was on a thermal protection system that was an integral part of the load bearing structure, providing commonality between materials for airframe structure and thermal protection, with a minimum reliance on exotic materials.[96] Nonetheless, a perception prevailed at NASA that the metallic heat shield concepts possessed some significant drawbacks. Many of the metallic materials required coatings, such as Sylvania R-512E, to provide oxidation protection. The coatings would

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94 Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Norman Chaffee (ed) ***Space Shuttle Technical Conference, Part 2*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985), pp 1062-1081.

95 McDonnell Douglas and Martin Marietta's Phase-B design proposed a titanium alloy hot-structure for the wings and fuselage, with the lower surfaces covered with columbium shingles. Cobalt superalloy was proposed for the control surfaces and the vertical tail was to made of a nickel superalloy. North American Rockwell's Phase-B design also adopted a radiant heat shield configuration, constructed of various metallic superalloys including columbium-129Y, Haynes-188 and Inconel-718. Grumman/Boeing's Alternate Phase-A design thermal protection system consisted of metallic panels backed with Micro-Quartz insulation; except for the rudder which was made of Inconel-718. Dennis Jenkins, ***Space Shuttle*** pp 76, 79, 93.

96 David Baker, 'Evolution of the Space Shuttle,' ***Spaceflight*** (July, 1973), pp 264-265.

have to be applied so thoroughly, both inside and outside (including fasteners), that it was feared that complicated inspection techniques between each flight would negate the advantages of commonality. Superalloys that did not require any coatings, such as nickel chrome (TDNiCr) were also considered, as they could withstand temperatures up to 2 400 degrees F, but the production rate of TDNiCr (around 10 000 pounds per year in 1970) was not sufficient to meet shuttle demands. Superalloys also showed a tendency to produce a rippling effect over the surface when repeatedly exposed to high temperatures, which could have a detrimental influence on aerodynamic stability. Metallic concepts, on the whole, were complex. Design features to minimize thermal distortion, intricate panel to panel joints, as well as the additional insulation blanket that would be required to protect the primary structure of the orbiter, all conspired against a metallic thermal protection system.[97]

In contrast to the complexity of the metallic systems, the nonmetallic heat shield concepts appeared to posses the advantage of design simplicity. Lockheed Missiles and Space Company's alternate proposal had an orbiter constructed from conventional aluminum with a thermal protection system comprised of titanium on the upper surfaces and its

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97 William Normyle, 'Shuttle Poses Dominant Challenge,' ***Aviation Week and Space Technology*** (June 22, 1970), pp 96-121; Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Norman Chaffee (ed) ***Space Shuttle Technical Conference, Part 2*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985), pp 1062-1081.

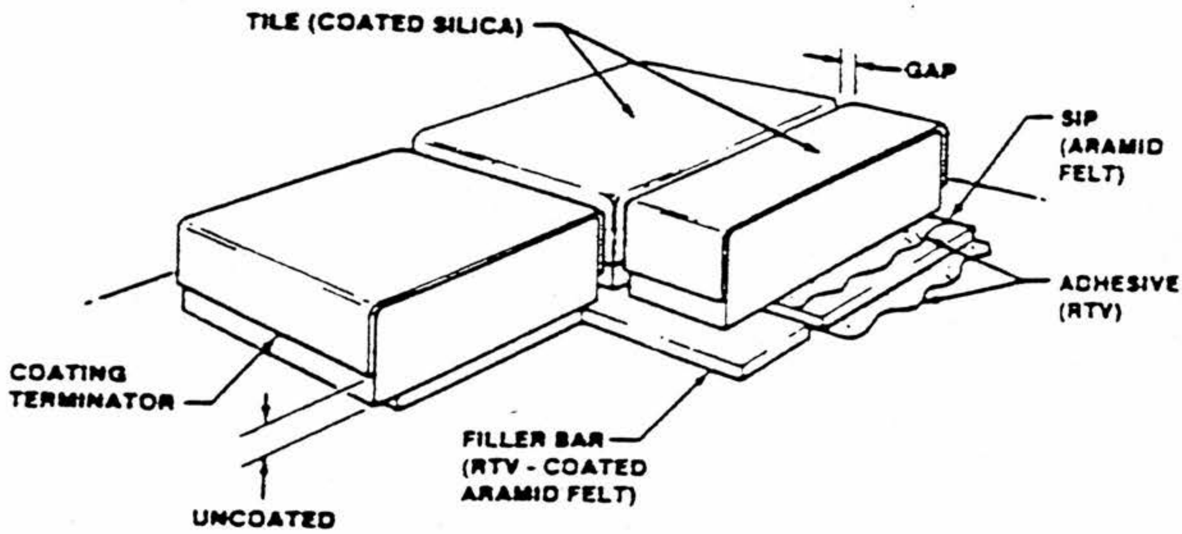
proprietary silica system, called LI-1500, on the lower surface.[98] It was the silica system that captured NASA's interest. Composed of tiles fabricated from 99.6 percent pure amorphous silica fibres derived from common sand, the system had the potential of offering a low density, low maintenance, reusable thermal protection system, which could be installed on a conventional airframe (see figure 4:9). While it was recognized that a major development programme would have to be undertaken to bring the nonmetallic materials out of the laboratory to a state of high production and vehicle application, the significant weight savings and inherent design simplicity influenced NASA to favour it as the primary material for the orbiter's thermal protection system.[99]

From 1970 to 1972 two nonmetallic reusable materials were under investigation by NASA and its contractors: a silica-base material (SiO_2) and a mullite ($3Al_2O_3$ SiO_2). Mullite was initially expected to exhibit a higher temperature capability because of its higher density; however, tests showed that the low density silica possessed a superior thermal performance due to the small fibre diameter material used in its formulation. The contractors working with mullite, McDonnell Douglas and General

98 'Non-Metallics Studied for Shuttle,' ***Aviation Week and Space Technology*** (January 18, 1971), pp 36-39; Dennis Jenkins, ***Space Shuttle*** p 89.

99 Samuel Beddingfield, interview with the author, July 31, 1995; 'Non-Metallics Studied for Shuttle,' ***Aviation Week and Space Technology*** (January 18, 1971), pp 36-39; Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Norman Chaffee (ed) ***Space Shuttle Technical Conference, Part 2*** pp 1062-1081; Dennis Jenkins, ***Space Shuttle*** p 119.

Figure 4:9.



SYSTEM DESCRIPTION.

Source: Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Chaffee Norman, (ed) *Space Shuttle Technical Conference: Part 2.*

Electric, failed to strengthen the material to levels compatible with the predicted thermal stresses of reentry. Silica was thus selected as the baseline material for the orbiter's thermal protection system in January 1973.[100]

Carbon-carbon was the only known material that showed potential for providing reuse capability for the high temperature areas (greater than 2 300 degrees F), such as the wing leading-edge and nose cap. NASA considered carbon-carbon a clear choice for the leading-edge applications because in test conditions it appeared far more durable than superalloys. Nevertheless, significant developments in coatings to prevent oxidation would have to be made to make carbon-carbon a multi-mission material.[101]

Eliminating Powered Atmospheric Flight.

Discussions on powered versus unpowered landings as an orbiter requirement had begun in late 1969. Powered landings, using air breathing jet engines, offered several potential advantages in operational flexibility, namely: that the orbiter could manoeuvre during atmospheric flight; be able to transport itself between launch sites and space Centers; offer the proviso of a testing capability during

100 William Hieronymus, 'Two Reusable Materials Studied for Orbiter Thermal Protection,' ***Aviation Week and Space Technology*** (August 23, 1973), pp 16-18; Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference***

101 ***Ibid.***

development flights; and provide an abort or go-around capability if the runway approach was inaccurate.[102]

Adding an atmospheric propulsion system also impacted on the shuttle's main propulsion systems by adding more weight to the vehicle.

> Well when you look at the jet engine you are carrying all that extra weight up to orbit, and there is about a 100 to 1 ratio thrust needed to propel it into orbit, plus the fuel it had.[103]

As a potential technical fix, low density liquid hydrogen fuel appeared to offer a partial solution to this problem. Hydrogen's lower mass and higher performance were significant advantages over conventional jet propellant (see figure 4:10). It did not require so many engines and had significantly less fuel mass, directly translated into higher payload lifting capability.[104]

Fuel mass was not, however, the only consideration. A hydrogen jet engine with a 500 hour life was not an existing technology and would have to be developed; elevating development costs and technical risks. The limited cruise range of the vehicle also implied numerous refuelling stops for long distance flights on ferry missions. In addition, since some of the projected shuttle missions would involve removal of the jet engines from the

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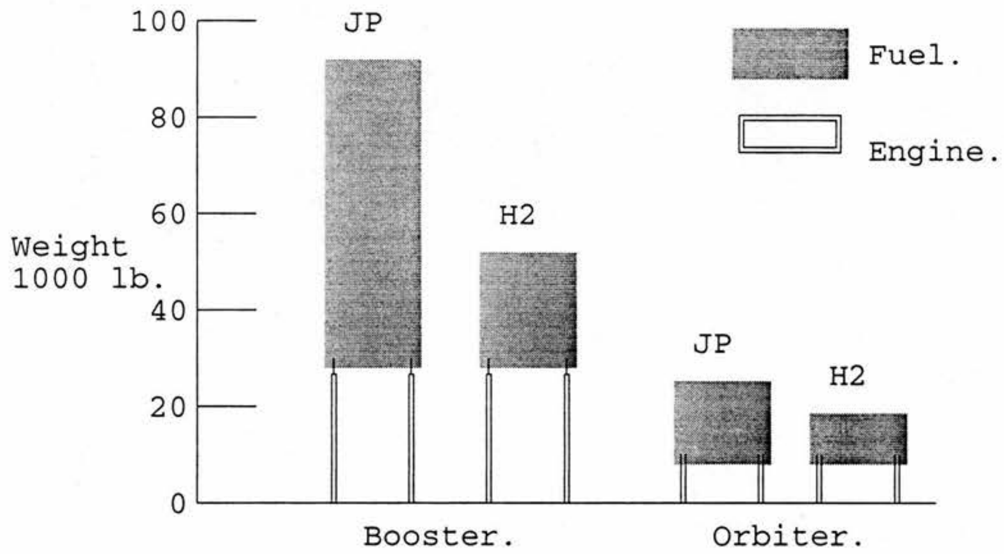
102 Scott Pace, ***Engineering Design and Political Choice*** pp 166-167.

103 Charles Donlan, interview with the author, June 7, 1995.

104 Michael Yaffee, 'New Technology Shuttle Engine Key,' ***Aviation Week and Space Technology*** (August 10, 1970), p 53.

Figure 4:10.



Source: NASA chart, taken from Michael Yaffee, 'New Technology Shuttle Engine Key,' ***Aviation Week and Space Technology*** (August 10, 1970), p 53.

orbiter to launch heavier payloads, the design had to allow for relatively easy mounting and removal with a minimum of inter-connecting hardware left on the orbiter.[105]

Pratt & Whitney and General Electric were both issued with hydrogen jet engine study contracts in June 1970. As concerns grew about the development and operational risks/costs of a hydrogen system, NASA extended both these contracts to re-examine conventional jet propellant systems. By 1971, Pratt & Whitney were proposing the use of their F401 engine and General Electric were championing their F101 engine. Minimum modifications to both engines would be necessary for utilization on the shuttle, but the contractors indicated that if conventional jet propellant was selected then their engines were well within existing technical capabilities.[106]

Germinating within NASA at the time was a movement to remove the jet engines from the shuttle's design completely. Carl Peterson of the Space Shuttle Project Engineering Office at Johnson, first gave voice to this movement in August 1970 when he issued a study change request to eliminate the jet engines from the shuttle system.[107] Peterson did not have the authority to change the requirement himself, but the request did stimulate

105 Scott Pace, ***Engineering Design and Political Choice*** pp 169-170.

106 ***Ibid.***

107 Carl Peterson, Manned Spacecraft Center Study Change Request, August 17, 1970 (NASA History Office Archive, Washington DC).

discussions about the role of jet engines in the baseline design. The central argument was that operational analysis had indicated that the addition of jet engines on the orbiter would only marginally increase reliability of a safe orbiter landing.

> [There was a] ... kind of mistaken views as to what constituted safety. You are carrying jet engines around in case you miss the airport. You have to think things through and say under what conditions are you going to want to that. If your guidance is so far away, you are not going to be near enough to that airport to use those jet engines anyway and if the guidance is right, as it has to be, you don't need the jet engines.[108]

Many within NASA were confident that a jet engine system on the orbiter would be superfluous because Gemini, Apollo, the X-15 and lifting body research had shown that guidance systems could pin-point vehicle entry very closely.[109] Dissent within the aeroplane community and among some test pilots and future shuttle astronauts was, however, evident; as LeRoy Day recalled:

> The aeroplane people were just in a state of shock. ... I remember giving a briefing to General Brown ... he said ... that was the most foolish thing he had ever heard of and NASA people didn't know what they were doing and they should talk to some aeroplane people. Well as a matter of fact NASA had a lot of aeroplane people and we were basing a lot of our thoughts and decisions about that on our research people ... at Edwards Air Force Base. ... We had already proven from a navigational standpoint that you

108 Charles Donlan, interview with the author, June 7, 1995.

109 Charles Donlan, interview with the author, June 7, 1995.

> could bring a vehicle back from space and come close to where you wanted to put down.[110]

Nonetheless, Donald Slayton, Director of Flight Crew Operations was unconvinced and advocated the retention of jet engines until confidence was gained with unpowered landings. In one memo Slayton commented:

> ... those in favor of unpowered operations cite FRC [Flight Research Center, Edwards] and AFFTC [Air Force Flight Test Center] experience ... as adequate evidence that the unpowered, piloted landing mode is practical and safe. Certainly, their work in this area is impressive. However, we believe that their experience only indicates that, given the unique conditions of the Edwards environment, unpowered landings can be accomplished safely if the vehicle can be maneuvered through reentry to certain initial conditions relative to the desired landing point. It is not intended, however, to operate the orbiter under the same conditions as exist at Edwards, and the effects of these differences need to be assessed operationally before the decision is made to remove the orbiter engines.[111]

Support for Slayton did not, as expected, come from the larger community of test pilots. They tended to give more weight to the experiences at Edwards, as Major Jerauld Gentry, an aerospace test pilot at the Air Force Test Center, Edwards Air Force Base, commented at the time:

> Many of us at Edwards feel that the requirement for the orbiter to have landing engines may be neither practical nor necessary. ... These

110 LeRoy Day, interview with the author, June 29, 1995.

111 Donald Slayton, memorandum to Shuttle Manger, August 25, 1970 (NASA History Office Archive, Washington DC).

feelings have not been looked upon with much favor, sympathy, or credibility.[112]

By the end of 1970, some 72 lifting body flights with significantly less subsonic lift to drag than the shuttle candidates had demonstrated unpowered and precisely controlled runway landings. Unpowered landings of a Boeing B-52, a Convair 990, a General Dynamics F-111 and a Lockheed F-104 were also offered as demonstrations of how a shuttle orbiter could safely land without the use of jet engines. A chief aspect of the unpowered landing technique that did cause some minor alarm, was the use of relatively steep, high-energy approaches, despite its appraisal as more accurate, safer, and actually less critical than most low-energy approaches.[113] Speed brakes, or a similar device, was thus deemed essential when using such a technique (see figure 4:11). The weight of a speed brake systems would be minimal and they required no fuel, but can be used much like engines to vary the landing pattern parameters.[114]

Negotiations between penalties on payload and enhanced reliability grew more intense as budget realities forced a minimization of programme development costs. As shuttle

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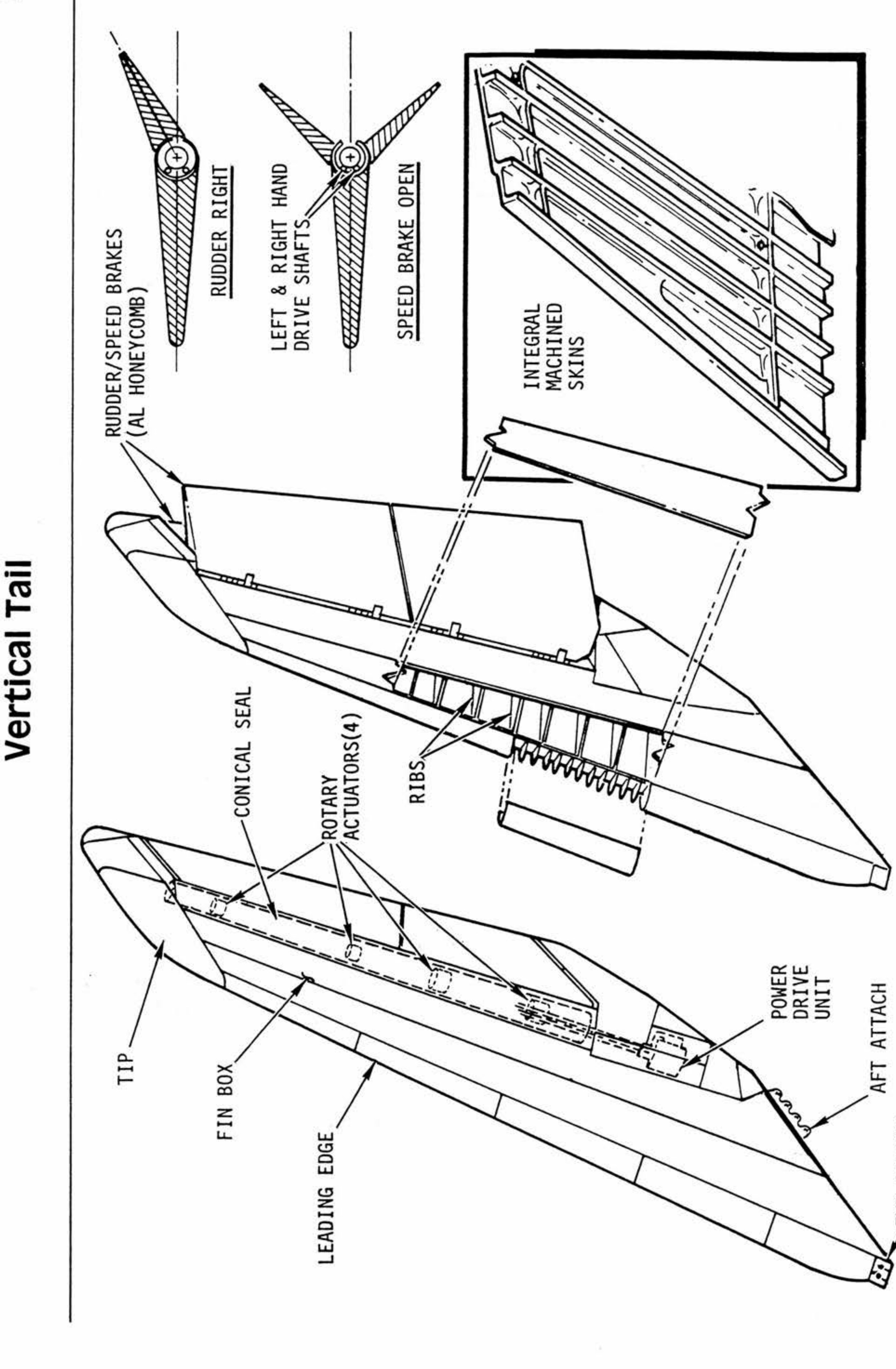
112 Jerauld Gentry, quoted in William Hieronymus, 'High-Speed Unpowered Landing Urged as Feasible for Shuttle,' ***Aviation Week and Space Technology*** (October 5, 1970), p 16.

113 Pilots had basically the same problem in positioning planes during a dive bombing approach. They would have to use a steep approach of about 10-25 degrees to intercept an aim point on the ground. The steeper the dive angle the greater the accuracy.

114 Scott Pace, ***Engineering Design and Political Choice*** pp 172-173; William Hieronymus, 'High-Speed Unpowered Landing Urged as Feasible for Shuttle,' ***Aviation Week and Space Technology*** (October 5, 1970), p 16.

Figure 4:11.
Source: W.H. Morita, (ed) ***Space Shuttle System Summary*** (Rockwell International, Space Systems Group, SSV80-1, May 1980).



designers looked for ways to maintain the shuttle's 65 000 pound lifting capability while reducing development costs and risks, the arguments in favour of deleting the jet engines grew in strength. NASA's shuttle managers eventually approved the deletion of jet engines on the baseline orbiter. Instead instructions were given to design "jet engine kits" for flight tests and ferry tasks. Although higher priority items had placed the jet engine issue on the back burner they remained a shuttle requirement up to 1974 when the Office of Manned Space Flight ultimately deleted them altogether.[115] The penalty of carrying jet engines and their fuel to orbit and back ultimately influenced the decision not to include them in a shuttle design. Considerable research on unpowered landings had offered an alternative and substantially cheaper option, but little consideration at this time had been given to logistics issues. The "jet engine kits" or a glider-type towing system were considered as possible solutions to ferry tasks and flight testing, but 'a space shuttle optimized for the orbital tasks does not readily adapt to horizontal takeoffs and cross-country atmospheric flight.'[116] A different solution, thus had to be derived.

115 ***Space Shuttle Requirements Document Level 1: Revision No.7***, October 7, 1974 (NASA History Office Archive, Washington DC), p 3.

116 Robert Thompson, ***Von Karman Lecture*** p 12.

The Selection of a Carrier Aircraft.

The prime motivations behind the removal of the orbiter's jet engines were the reduction in overall system complexity and increase payload lifting capacity by reducing system weight. NASA's engineering community had persuaded the agency's upper echelons as to the feasibility of the idea and had instilled confidence in a glider concept. Nevertheless, the result of this decision left NASA with a major quandary. Without a means of transporting the orbiter from the manufacturing site at Palmdale, California to Kennedy in Florida, NASA would be faced with the real problem of having built the proverbial "boat in the basement".[117]

A different, but related problem had also arisen because of the loss of the orbiter's jet engines; that of being able to flight test the orbiter. A series of subsonic flight tests was considered necessary by a number of NASA officials to evaluate the orbiter's atmospheric flight characteristics, especially during the planned steep unpowered approach to landing. To have the first landing of the orbiter conducted from reentry on its first orbital test flight was considered an extreme option.[118]

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117 Ivy Hooks, David Homan, Paul Romere, 'Aerodynamic Challenges of ALT,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2*** p 295.

118 ***Ibid.*** p 296; 'Giant Aircraft Would Lift Shuttle Orbiter,' ***Aviation Week and Space Technology*** (February 4, 1974), pp 38-41.

As a possible solution to both these problems, a few engineers from Johnson suggested to the Orbiter Project Manager, Aaron Cohen, that the orbiter could be ferried by another aircraft, in a mode similar to that used to launch the X-15. Cohen, however, was far from impressed by the idea, as he recalled:

> Well one day some of our engineers came to me and said Aaron, we think we can fly [the orbiter] on top of [another aircraft] and ferry it. I said that's the dumbest idea I have ever heard of, I don't even want to hear about this. I said, you guys get out of my office ... I am too busy to talk about those dumb ideas.[119]

Nonetheless, the engineers were very persistent and set out to convince upper management that the idea was indeed workable.[120]

By early 1974, negotiations had reached a point where NASA's top management gave approval for a number of feasibility studies into the carrier aircraft idea. Numerous concepts were examined, but as the year progressed three configurations emerged as the most likely candidates: (i) development of a new carrier aircraft named the Virtus; (ii) use a modified Air Force Lockheed C-5A; or (iii) use of a modified Boeing 747.

Virtus was a new aircraft design proposed by John Conroy, designer of the Guppy aircraft that were used by NASA to transport major elements of the Saturn/Apollo

119 Aaron Cohen, interview with the author, September 8, 1995.

120 Aaron Cohen, interview with the author, September 8, 1995.

system. NASA officials, therefore, took the proposal seriously and contracted a feasibility study through the Langley Research Center. With an overall length of 280 feet, a wing span of 450 feet and a height of 100 feet, Virtus, a latin word used by the Hungarians to denote striving for success in the face of overwhelming odds, was an apt name for this giant aircraft. Preliminary estimates put the cost of building two Virtus aircraft at around $25 million. Despite its innovative structure, the Virtus design utilized many existing aircraft subsystems to keep costs low. A cockpit and forward fuselage section from a C-97 was envisaged for the crew module. The landing gear and other high development cost items would have been taken from surplus Boeing B-52 bombers. The Virtus was to be constructed from conventional aluminum and the design reduced curved surfaces to an absolute minimum, thus simplifying both fabrication and construction.[121]

The two alternative concepts were modifications to aircraft already in existence. Lockheed and Boeing were both receiving funding, equal to $100 000 per month, to study the feasibility of using either a Lockheed C-5A, provided by the Air Force or a Boeing 747. Lockheed claimed that its configuration would not require any major structural modifications nor any significant subsystem changes. Boeing's proposal, on the other hand, called for

121 'Giant Aircraft Would Lift Shuttle Orbiter,' ***Aviation Week and Space Technology*** (February 4, 1974), pp 38-41.

substantial modifications, which would add over 9 000 pounds of structure to the 747 aircraft. The two aircraft were both equally capable of airlifting the orbiter, but in early 1974 NASA favoured the C-5A concept because the plan involved the Air Force providing the carrier on a demand basis as part of its participation in the shuttle programme. The Air Force however, were unable to make such a guarantee. The House of Representatives had cut the $58.5 million request for the stretched Lockheed C-141 and the Civil Reserve Air Fleet modification programmes, from the Air Force's FY 1974 budget. The move gave rise to some concern at NASA, because it could place a heavier operational demand on the C-5A fleet and thus reduce the availability of the aircraft for shuttle purposes.[122]

Vitrus had a number of perceived advantages. The configuration allowed the orbiter to be suspended between the two fuselages, which simplified the problem of separating the orbiter from the aircraft during the planned approach and landing tests. Dropping the orbiter from the Virtus would be no different from the types of tests NASA's Flight Research Center had been conducting at Edwards for years.[123] Virtus was nonetheless short lived. The idea of developing a new aircraft for the sole purpose of

122 Donald Fink, 'Carrier Designs for Space Shuttle Orbiter Being Refined,' ***Aviation Week and Space Technology*** (April 29, 1974), pp 54-62.

123 'Giant Aircraft Would Lift Shuttle Orbiter,' ***Aviation Week and Space Technology*** (February 4, 1974), pp 38-41.

transporting the orbiter was considered unreasonably costly and was thus quickly abandoned.[124] NASA also doubted whether the Vitrus could be developed on time for the approach and landing tests, scheduled for 1977.[125]

Although NASA's top management were still concerned about the safety of separation of the shuttle from either the C-5A or the 747,[126] the 747 was eventually chosen, because of concern about dedication of C-5A's for NASA's use.[127] NASA's selection of the 747 caused some minor concern within Congress. Senator Barry Goldwater expressed 'grave doubts' over its success and made it known that he thought that the Vitrus concept was the better choice.[128]

Aerodynamic Design and the Orbiter's Wings.

When NASA embarked on its shuttle development programme, behind them lay a fairly mature discipline on the construction and flight characteristics of aircraft design. Aerodynamics had come a long way from its empirical roots at the start of the twentieth century. Experimental data,

124 Ivy Hooks, David Homan, Paul Romere, 'Aerodynamic Challenges of ALT,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2*** p 296.

125 Letter from James Fletcher to Senator Barry Goldwater, October 4, 1974 (NASA History Office Archive, Washington DC).

126 Letter from William Schneider, Acting Associate Administrator for Manned Space Flight, to George Low, NASA Deputy Administrator, April 12, 1974 (NASA History Office Archive, Washington DC).

127 Letter from George Low to John McLucas, Secretary of the Air Force, July 3, 1974 (NASA History Office Archive, Washington DC).

128 Letter from Senator Barry Goldwater to James Fletcher, October 12, 1974 (NASA History Office Archive, Washington DC).

mathematical models and flight experience all supported a firm foundation of empirical and theoretical knowledge in aerodynamic design.[129] Nevertheless, inherent within the shuttle's design lay numerous contradictions; and nowhere did these contradictions reveal themselves more forcibly than in the aerodynamics of the shuttle's return flight.

NASA and its contractors were faced with constructing a vehicle that had to realize many conflicting requirements. The orbiter had to perform the task of reentry like a spacecraft and yet land on a runway like an aircraft. This meant designing an aerodynamic configuration that would function through the entire atmospheric flight regime; from hypersonic through to subsonic and down to a landing velocity. Each speed regime demands quantifiable differences in aerodynamic design and those above hypersonic were largely unknown. Indeed, the orbiter was going to be the first winged vehicle ever to fly through the hypersonic speed regime. The programme thus, presented the first real technological test of theoretical high speed flight, as Johnson's Director, Christopher Kraft recalled:

> The ability to perform a reentry from Mach 26 to touch down speeds ... through the entire Mach number regime, particularly from Mach numbers of 10 to 1, that was ... a technical feat, ... which nobody had ever done before; and one which there was no capability to run [a] test [on] in the world, ... in wind tunnels or anything else. We

[129] Walter Vincenti, ***What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*** (Baltimore, The John Hopkins University Press, 1993), especially Chapter 1.

had to do that by rope and by mathematics and by guessing.[130]

So despite the maturity of aerodynamics, precedents did not exist to facilitate many of the design requirements.[131] In the domain of aerodynamics, the return flight was going to be fraught with difficulties.

> At the time, the magnitude of the task seemed overwhelming considering the size of the flight envelope the variety of control devices, control modes and control tasks.[132]

In contrast with other modes of transportation, such as ships, cars and trains etc, the problems associated with the stability and controllability of an aircraft take a position of preeminence in its design, because it has to move within three dimensional space as opposed to two.[133] Determining design issues were: wing design, wing-body integration and integration of aerodynamic and flight control requirements. For the orbiter (as with all aircraft), wing design was key, because of its influence on vehicle weight, thermal environment, aerodynamic stability,

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130 Chris Kraft, interview with the author, September 1, 1995.

131 James Young, Jimmy Underwood, Ernest Hillje, Arthur Whitnah, Paul Romere, Joe Gamble, Barney Roberts, George Ware, William Scallion, Bernard Spencer, James Arrington, Deloy Olsen, 'The Aerodynamic Challenges of the Design and Development of the Space Shuttle,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985), pp 209-263.

132 David Gilbert, 'Space Shuttle Handling Qualities,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** p 137.

133 Bernard Etkin, ***Dynamics of Flight: Stability and Control*** (New York, John Wiley & Sons Inc, Second Edition, 1982), p 3.

buffet characteristics and gliding and landing performance.[134] Wing shape was also important because it determined the vehicle's aerodynamic performance. Decisions on shape were, therefore, made with the desired performance in view. To define the shape of a wing, aerodynamicist need to make a decision about the planform (the outline of the wing when viewed from above) and the profile of the fore and aft sections, referred to as the airfoil. Two kinds of forces exert on the surface of a wing; pressure at right angles to the surface, known as lift and, skin friction tangential to the surface, known as drag. Lift depends almost entirely on the distribution of pressure. Drag, by contrast, depends primarily on the skin friction, which exists by virtue of the viscous flow in a thin boundary layer next to the surface of the wing.[135] The problem confronting the aeroplane designer is how to shape a wing that will obtain the optimum lift and drag characteristics needed for the vehicle's performance requirements. Wing design for the orbiter was further complicated however, because it had to satisfy the conflicting aerodynamic characteristics of the entire flight regime. Stuart Treon, chief of the Experimental Investigations Branch at the

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134 James Young, Jimmy Underwood, Ernest Hillje, Arthur Whitnah, Paul Romere, Joe Gamble, Barney Roberts, George Ware, William Scallion, Bernard Spencer, James Arrington, Deloy Olsen, 'The Aerodynamic Challenges of the Design and Development of the Space Shuttle,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985), pp 209-263.

135 Walter Vincenti, ***What Engineers Know and How They Know It*** pp 18, 34; A.C. Kermode, ***An Introduction to Aeronautical Engineering: Vol 1, The Mechanics of Flight*** (London, Sir Issac Pitman & Sons, Ltd, 1940).

Aimes Center, told *Aviation Week and Space Technology* at the time, that the aerodynamic problems posed by the shuttle were 'extremely unusual'.[136]

As highlighted above, the debate over wing design took on a political edge as well as technical matters. Orbiter configurations emanating from Johnson had adopted a straight wing design, essentially for simplicity. During the reentry phase of flight the orbiter would be positioned at a very high angle of attack, almost 60 degrees, which produced very high drag values to slow velocity. The vehicle would remain at this attitude until about 40 000 feet, at which point velocity would have been reduced to less than 300 feet per second. The nose would then be pushed down and the vehicle would go into a dive until it reached adequate velocity for level flight. Max Faget, the champion of the straight wing design, maintained that the important advantage of this configuration was that it minimized heating rates and reduced overall system weight. At such a high angle of attack, only the lower surfaces would be directly exposed to the on-coming air flow, which reduced the amount of protective insulation.[137]

Nevertheless, the low crossrange produced by Faget's straight wing design combined with a high angle of attack at reentry was unacceptable to the Air Force. Demand for a

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136 Richard O'Lone, 'Shuttle Test Pace Intensifies at Aimes,' ***Aviation Week and Space Technology*** (June 24, 1974), p 71.

137 Scott Pace, ***Engineering Design and Political Choice*** pp 137-139.

return to runway after a single orbit dictated a relatively shallow angle of attack and the high lift of a delta wing to produce the desired 1500 nautical mile crossrange. Crossrange was not the only point of contention between the straight and delta wing designs. Slight centre of gravity shifts and balance consideration tended to move the straight wings aft, closing the gap between the tail and the wing. Many of the early orbiter designs carried internal fuel tanks, resulting in the centre of gravity being near the middle of the vehicle's length. It thus made sense to have the wings in roughly the same position for stability. But when the external tank was introduced and the weight of the orbiter's main engines grew, arguments were raised that Faget's design, with its long leading and trailing edges, would incur more heating problems than a shorter vehicle with lower aspect ratio delta wings. Wind tunnel and drop tests of models also indicated that the straight wing design might be dynamically unstable. The tests suggested the possibility of a divergent oscillation in a falling-leaf mode and a tendency for the orbiter to flat spin. Further analysis did show that the motions could be easily dampened by reaction control thrusters, but performing complex control commands during reentry was not favoured by many at NASA or the Air Force.[138]

138 ***Ibid.*** pp 141-143.

Although both configurations were technically feasible, Air Force pressure eventually swayed NASA away from the straight wing design. Despite the weight penalty and increased complexity of thermal protection, in the political arena Air Force support for the programme was deemed far more important. As various shuttle concepts were winnowed out, an orbiter configuration incorporating a blended delta wing was eventually adopted in August 1972.[139]

A series of wind-tunnel tests conducted during 1972, indicated that the original configuration did not meet NASA's landing performance requirements. Initially NASA had not stipulated a landing velocity on which to design the orbiter's wings, but midway through Phase-B the Office of Manned Space Flight defined a subsonic design velocity of 165 knots. This would produce a touch down velocity of between 180 to 190 knots, which was well within the state of the art in landing gear systems. The need to meet these requirements, then led to a re-configuration of the wing in late 1972. In-house studies by NASA and activity at Grumman indicated that a double-delta planform produced a more efficient lifting surface than the blended delta and had exceptional landing performance. In late 1972 NASA instructed Rockwell to incorporate a double delta wing

139 James Young, Jimmy Underwood, Ernest Hillje, Arthur Whitnah, Paul Romere, Joe Gamble, Barney Roberts, George Ware, William Scallion, Bernard Spencer, James Arrington, Deloy Olsen, 'The Aerodynamic Challenges of the Design and Development of the Space Shuttle,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985), pp 209-263.

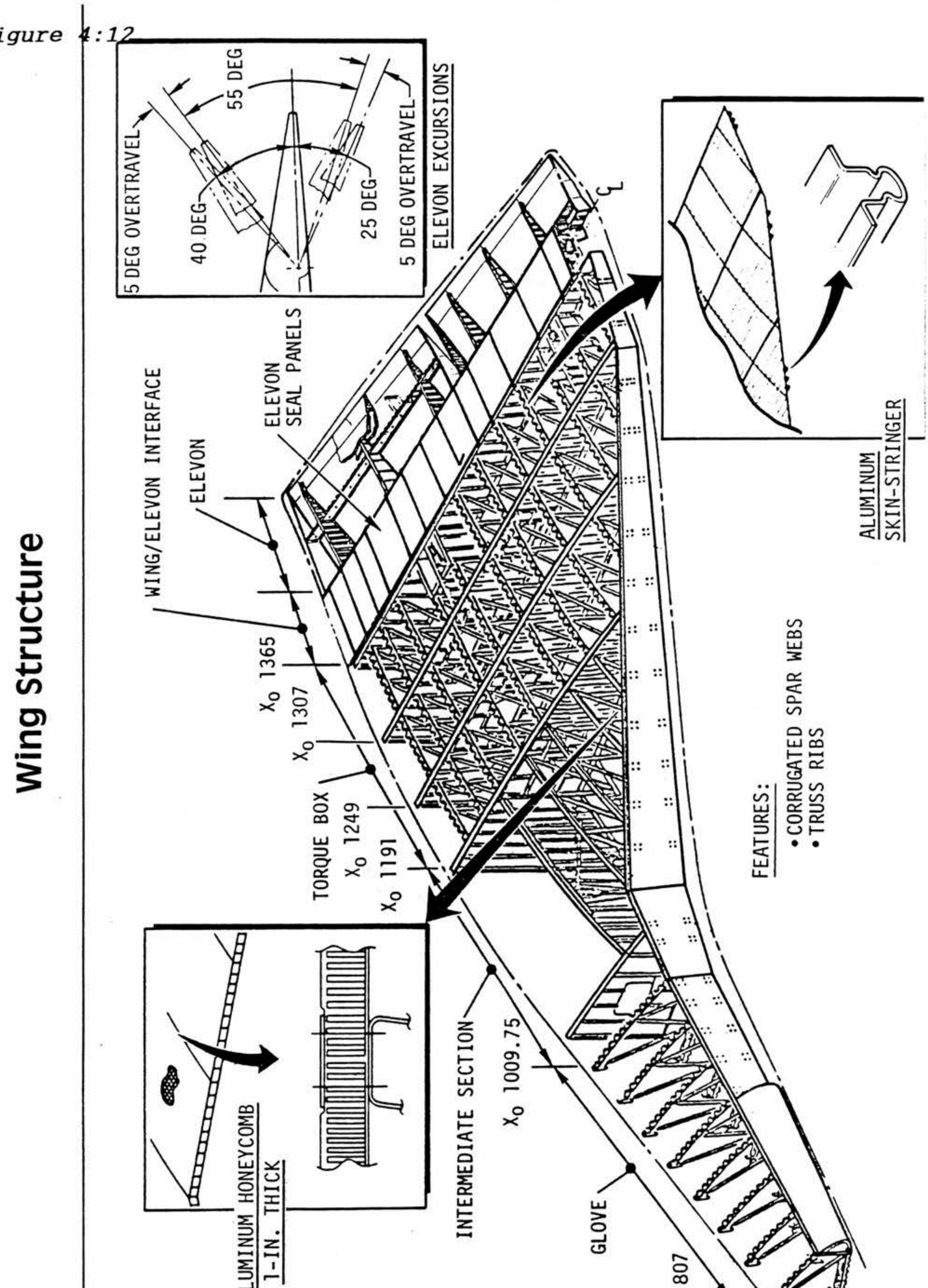
design (see figure 4:12). In addition, the double-delta wing allowed for aerodynamic stability and trim to be adjusted by modifying the lightly loaded forward delta (glove). This simple control of aerodynamic features meant that the design of the main delta wing box could be frozen and any centre of gravity shifts or aerodynamic stability problems could be corrected by glove modification, thereby minimizing the impact on the shuttle programme as a whole.[140]

Simplification was a fundamental principle of aerodynamic design because of the inherent complexity and contradictory nature, of the orbiter's return flight trajectory. As such, the sophisticated geometric techniques of past aerodynamicists were not deemed appropriate solutions for the orbiter's design; as Space Shuttle Manager, Robert Thompson recalled:

> Aerodynamic oriented people ... had done a lot of work on trying to shape [the] vehicle very cleverly so that it had good aerodynamic characteristics through the entire speed range; and its a very broad speed range because you go from hypersonic speeds down to supersonic speeds to subsonic speeds and the aerodynamic characteristics change in those regimes, such that something shaped to fly good in one regime isn't necessarily good to fly in another. So we avoided getting into a lot of fancy shaping of the vehicle, or a lot of variable geometry kind

140 Richard Kline, interview with the author, May 31, 1995; James Young, Jimmy Underwood, Ernest Hillje, Arthur Whitnah, Paul Romere, Joe Gamble, Barney Roberts, George Ware, William Scallion, Bernard Spencer, James Arrington, Deloy Olsen, 'The Aerodynamic Challenges of the Design and Development of the Space Shuttle,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985), pp 209-263.

Figure 4:12



Source: W.H. Morita, (ed) *Space Shuttle System Summary.*

> of solutions by just brute forcing our way through.[141]

Very early on in the programme, therefore, NASA had decided to incorporate a computer-controlled flight control system, which permitted the required vehicle stability and handling qualities to be artificially produced.

> We actually used the control system on the vehicle to stabilize it in many cases. We didn't worry about giving it a basic airframe stability.[142]

The integration of aerodynamic control requirements through an automated system was thus of major importance in meeting flying quality goals in all the flight regimes. Augmentation of the aerodynamic stability through the automated flight control system also allowed for a minimization of vehicle weight as affected by control surface arrangement, size and actuator requirements. Traditionally, a relatively large empennage is required to provide the requisite vehicle directional stability. However, a smaller empennage, which contributed significantly to reducing overall system mass could be utilized because of the computer control system.[143]

Aerodynamic design was also influenced by a number of programmatic decisions made during the Phase-B studies. The most significant of these was the inclination towards and

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141 Robert Thompson, interview with the author, September 7, 1995.

142 Robert Thompson, interview with the author, September 7, 1995.

143 Robert Thompson, interview with the author, September 7, 1995.

consequential selection of, a silica tile thermal protection system rather than a metallic hot structures system.[144] This design decision dictated that the initial entry angle of attack should be as high as possible (around 30 to 50 degrees) to minimize reentry heating. A metallic hot structures system would have allowed for a more shallow trajectory.[145] Nevertheless, the Air Force's fiercely fought crossrange specification impose an angle of attack of 30 degrees or lower to achieve the required hypersonic lift to drag ratio. To reduce reentry heating and thus increase the lifespan of the thermal protection system, a compromise position was arrived at and an angle of attack profile of 40 degrees was chosen for all missions not requiring the high crossrange. The design of the thermal protection system also dictated that the orbiter's surface was composed mainly of large flat areas, limiting curvature to smaller areas between the flat ones. This maximized the use of uniform dimension tiles, which would minimize both production and insulation costs. Wing and body integration was important to obtain a balanced aerodynamic configuration capable of trim and control over the entire speed range and in minimizing thermal environment due to interference flow effects. The orbiter's fuselage

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144 James Young, Jimmy Underwood, Ernest Hillje, Arthur Whitnah, Paul Romere, Joe Gamble, Barney Roberts, George Ware, William Scallion, Bernard Spencer, James Arrington, Deloy Olsen, 'The Aerodynamic Challenges of the Design and Development of the Space Shuttle,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985), pp 209-263.

145 Frank Reagan, ***Re-Entry Vehicle Dynamics*** (New York, American Institute of Aeronautics and Astronautics, Inc, 1984).

dimensions had been largely fixed by the size of the payload bay, while aerodynamic and aerothermodynamics considerations established fore-body shape and local contours.[146]

In March 1974 a new baseline configuration for the orbiter emerged. Further wind tunnel tests, however, demonstrated that this configuration was also not workable. The tests showed difficulty in providing trim capability at the forward centre of gravity in the supersonic flight regime. In addition, the tests indicated that the blunt fuselage nose resulted in early transitional flow and high temperatures along the lower body surface. The wing camber and thickness distributions, designed for maximum subsonic performance, also led to local fairings on the lower wing and fuselage surfaces, which caused high local heating. These findings led to a further modifications to the orbiter's aerodynamic configuration and a refined shape based on the first phase of wind tunnel tests was eventually selected in February 1975.[147]

Negotiations about form and function shaped matters of detail as well as matters of the whole. Political,

146 James Young, Jimmy Underwood, Ernest Hillje, Arthur Whitnah, Paul Romere, Joe Gamble, Barney Roberts, George Ware, William Scallion, Bernard Spencer, James Arrington, Deloy Olsen, 'The Aerodynamic Challenges of the Design and Development of the Space Shuttle,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985), pp 209-263.

147 ***Ibid.***

technical, material and organizational factors all fused to shape each of the sub-systems reviewed and, thus, the shuttle itself. Once each of the parts was defined, however, they had to be reconnected into the whole. And an important part of the reconnection involved the bringing together of humans and things in a specific organizational form. The fabrication of large technological systems entails modes of enforcement over social order.

Chapter 5

Constructing the Assemblage

> Organizations are constructed to satisfy particular needs arising out of their environments. They have structures and these determine their shape, their precise hierarchical and authority character, their occupational distribution with its rewards and status attributes, their procedures and regulations and their methods of control over the distribution of resources in general.[1]

Ascension of the Lead Center.

Although many elements of shuttle technology had begun to take shape by early 1970, the Office of Manned Space flight had not reached a decision on managerial arrangements or organizational structures for the programme. Many within NASA assumed that research and development of the original two-stage configuration would be evenly split between Marshall and Johnson; with Marshall controlling the booster and Johnson the orbiter. The only part of the debate believed to be left open was whether to give both the booster and the orbiter to one company, or have them divided into separate research and development programmes using two contractors. Major elements of the aerospace industry had thus combined to form cooperative amalgams, which forged themselves around the two portions of the

1 V.L. Allen, ***Social Analysis: A Marxist Critique and Alternative*** (Shipley, The Moor Press, 1975), p 273,

shuttle system.[2] Nevertheless, pressure to establish an alternative programme management structure was exerted long before NASA was forced to change the shuttle configuration.

Discussions between the Office of Manned Space Flight and the Phase-B contractors about the philosophy of industry participation, programme management, and organizational structures were conducted at the end of 1970. Differing view points were put forward from both McDonnell Douglas and North American Rockwell on management structure and style, but it was clear that both contractors did not favour NASA's current arrangements.[3]

> The Douglas personnel seem to feel that separate orbiter and booster contracts administered independently by separate NASA Centers would be an undesirable arrangement for the government and industry and would lead to administrative chaos as well as excessive funding requirements. ... [North American Rockwell] also expressed concern about having independent orbiter and booster contracts separately administered by two NASA Centers. ... [I]t is apparent that North American would like to see a strong central program office some-where within NASA.[4]

The Deputy Associate Administrator for Manned Space Flight, Charles Donlan, agreed with the Phase-B contractors and urged a restructuring of programme management structure to provide greater coordination among the Centers. He put

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2 'Shuttle Group Readies Proposal Requests,' ***Aviation Week and Space Technology*** (January 19, 1970), pp 17-18; David Baker, 'Evolution of the Space Shuttle: Part 1,' ***Spaceflight*** (June, 1973), p 203. Boeing joined with Lockheed, McDonnell Douglas teamed with Martin Marietta, Pan-American and TRW; and North American Rockwell, who initially bid alone later joined forces with General Dynamics.

3 Charles Donlan, memorandum for the record, trip report, visit to Phase-B contractors with Dale Myers, December 21, 1970, dated, January 4, 1971 (NASA History Office Archive, Washington DC).

4 ***Ibid.***

forward a plan to decentralize management by incorporating a *lead Center* concept. Such a management style, he argued would preclude some of the conflicts between the field Centers that had plagued the Apollo programme.[5]

Confrontation between the field Centers had its roots in the establishment of NASA. A number of already existing organizations, each with their own histories, traditions and customs, were united during the post-Sputnik paranoia to form the single space agency. NASA, more closely resembled a confederation of organizations, with the field Centers behaving like small fiefdoms, rather than duplicating an absolutist dominion. This decentralized structure, in which engineers and scientists carried out their work in well-insulated Centers, was not conducive to the grand project of Apollo and resulted in a mismatch between the mission and the institutional interests of the various field Centers. Two major reorganizations thus took place early in Apollo, which centralized the programme within the Office of Manned Space Flight and led to the creation of the Johnson Space Center at Houston, Texas.[6] Nonetheless, inter-center rivalries continued.

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5 Henry Dethloff, ***Suddenly, Tomorrow Came... A History of the Johnson Space Center*** (Lyndon B. Johnson Space Center, The NASA History Series, NASA SP-4307, 1993), p 227.

6 Howard McCurdy, ***Inside NASA*** chapter 1, pp 96-97; Walter McDougall, ***The Heavens and the Earth*** pp 373-377; Dale Carter, ***The Final Frontier*** pp 203-207; Erasmus Kloman, 'NASA Organization and Management from 1961 to 1985: the Vision and the Reality' Francis Hoban, (ed) ***Issues in NASA Program and Project Management*** (Washington DC, Office of Management, Scientific and Technical Information Division, NASA SP-6101(02), 1989) pp 35-43; Henry Lambright, ***Powering Apollo*** pp 106-107, 109-111, After the 1967 Apollo fire NASA Administrator, James Webb centralized the programme further taking control of the programme himself, see pp 157-162.

One of the most striking divisions was between the 'nose-cone' people and the 'launch vehicle' people.[7]

> There was always that rivalry between the launch vehicle and spacecraft people. Some snobbery developed, the attitude was that the spacecraft people were more responsible for the results of the mission than the launch vehicle guys were, you know your the truck, and we are the real reason for you being here.[8]

To resolve this conflict Marshall was given control over propulsion and launch vehicles, Kennedy managed vehicle assembly and launch activities and Johnson governed over spacecraft. Spacecraft was, however, presumed by Johnson to cover all human space activities and it wanted control over operational activities as well. The first mission control for human space flight was located at Kennedy, so when Johnson was established and mission control moved there, many at Kennedy saw it as a political manoeuvre, which removed control from Kennedy. Jealousy and suspicion thus grew between Johnson and Kennedy; and the close relationship between Kennedy and Marshall, fashioned through their common heritage, resulted in the rift between launch vehicle and spacecraft growing much wider. As Apollo progressed each Center sought to build its own capability and expand its areas of competence to compete for future projects. Attempts by the Centers to expand their remits often led to complaints that each were usurping the others'

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7 George English, interview with the author, July 26, 1995.

8 George English, interview with the author, July 26, 1995.

responsibilities.[9] As equal partners in the Apollo programme, friction between the Centers continually revolved around jurisdiction, as Robert Freitag, Deputy Director of the Advanced Programs Office, recollected.

> If there was ever an interface or a parallel activity then competition always turned up. I spent half of my life in NASA listening to Johnson people telling me what's wrong at Marshall and vice versa.[10]

In an endeavour to avoid any future discord between the Centers over control of the shuttle programme, the Office of Manned Space Flight wanted to establish early on the programmes lines of responsibility and priorities.

> Well there had been for a long time in NASA ... a conflict between the various organizations. Whose running the show? And even in NASA, the Johnson Space Center, its missions were known as Apollo/Saturn ... and at Marshall, they were Saturn/Apollo and so to avoid that kind of conflict and we had a goodly amount of that right early in the program, it was concluded the best thing to do was establish a *lead Center* and put the program office there and give them the overall responsibility for running the program ... on that basis.[11]

The logical choice for the Office of Manned Space Flight was to place Johnson in the role of lead Center.

> The idea was the biggest department was the orbiter. You have to get that thing up there to be useful, everything else is subordinate to it, ... the reason [why Johnson was chosen] was they had the orbiter, keep your eye on the orbiter all the time because nothing else matters, as a

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9 George English, interview with the author, July 26, 1995; Robert Freitag, interview with the author, June 5, 1995; Erasmus Kloman, 'NASA Organization and Management from 1961 to 1985' p 37; Henry Dethloff, ***Suddenly, Tomorrow Came*** p 108.

10 Robert Freitag, interview with the author, June 5, 1995.

11 James Jackson, interview with the author, July 12, 1995.

> result the management structure reflected those changes.[12]

Johnson were, of course, in full accord with the plan as it saw itself as the best organization to manage the programme.

> I think it was natural that the lead Center kind of requirement and the lead Center selection would be the Johnson Space Center because it was where all the experience was.[13]

Outside of Johnson, though, the lead Center approach did not find much favour.

> There were others who wanted what they felt was an Apollo type management where the command module was separate from the Saturn V itself. Well that was a different era and they were equal partners in reporting to Headquarters. I had felt from the very beginning that the shuttle was not an equal partner, if there were compromises to be made they ought to be made in favour of the orbiter. Well the people responsible for the [other systems] didn't feel like that, they wanted an equal say.[14]

This pattern of conflict plagued NASA's internal workings across a whole range of programmes and, as future Administrator, James Beggs (1981-1986) recalled, continued on throughout the shuttle programme:

> Each Center at NASA has its own culture, its own personality and each thinks it can do the job better than the others. ... There's always been a bit of an overlap and they will fight to hold on to whatever piece of their pie they think is important to them.[15]

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12 *Ibid.*

13 Christopher Kraft, interview with the author, September 1, 1995.

14 Charles Donlan. interview with the author, June 7, 1995.

15 James Beggs, interview with the author, June 6, 1995.

Charles Donlan eventually convinced the Associate Administrator for Space Flight, Dale Myers, on the virtue of the lead Center plan[16] and in June 1971, the Office of Manned Space Flight confirmed that Johnson would have management responsibility for programme control, overall systems engineering and systems integration, and overall responsibility and authority for the definition of those elements of the total system which interact with other elements. The Center also had primary development responsibility for the orbiter. Marshall would be responsible for the development of the booster stage and the main engines and Kennedy would design and direct launch and recovery facilities. NASA Headquarters was to manage the overall programme and have primary responsibility for the assignment of duties, basic performance requirements, allocation of funds and control of the major milestones (See Figure 5:1).[17] Robert Thompson, who had been appointed Space Shuttle Program Manager in April 1970, was given responsibility as overall programme manager once the lead Center system had been put in place, as Robert Thompson recalled:[18]

> Charles Donlan ... and Dale Myers, they ... endorsed the concept of having the Program Manager as lead Center, and that's when they

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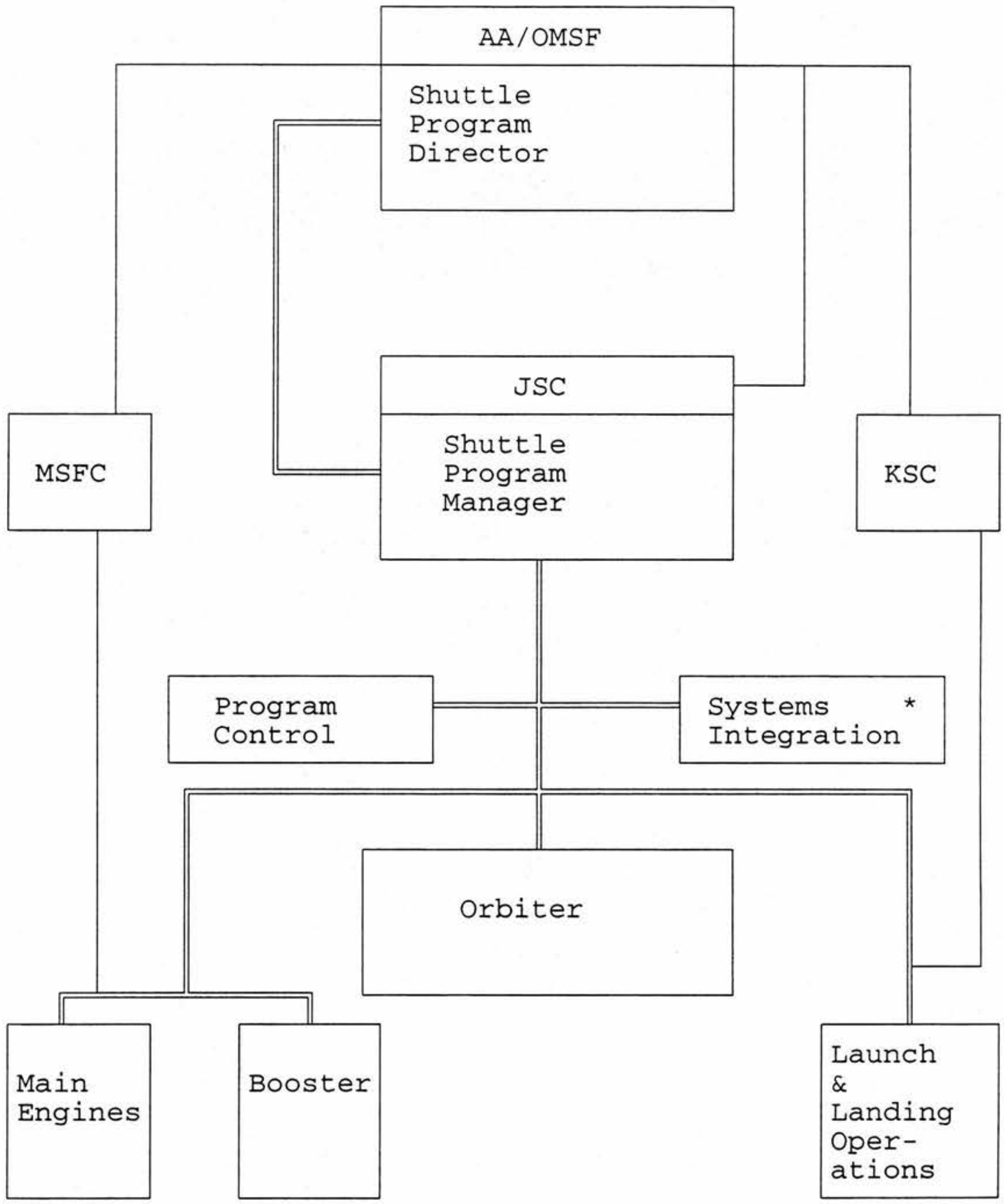
16 Charles Donlan, interview with the author, June 7, 1995.

17 Dale Myers, management instruction, space shuttle program management, July 12, 1971 (NASA History Office Archive, Washington DC); Henry Dethloff, ***Suddenly Tomorrow Came*** p 227.

18 Robert F. Thompson, interview with the author, September 7, 1995.

Figure 5:1.

Space Shuttle Management Relationships 1971.

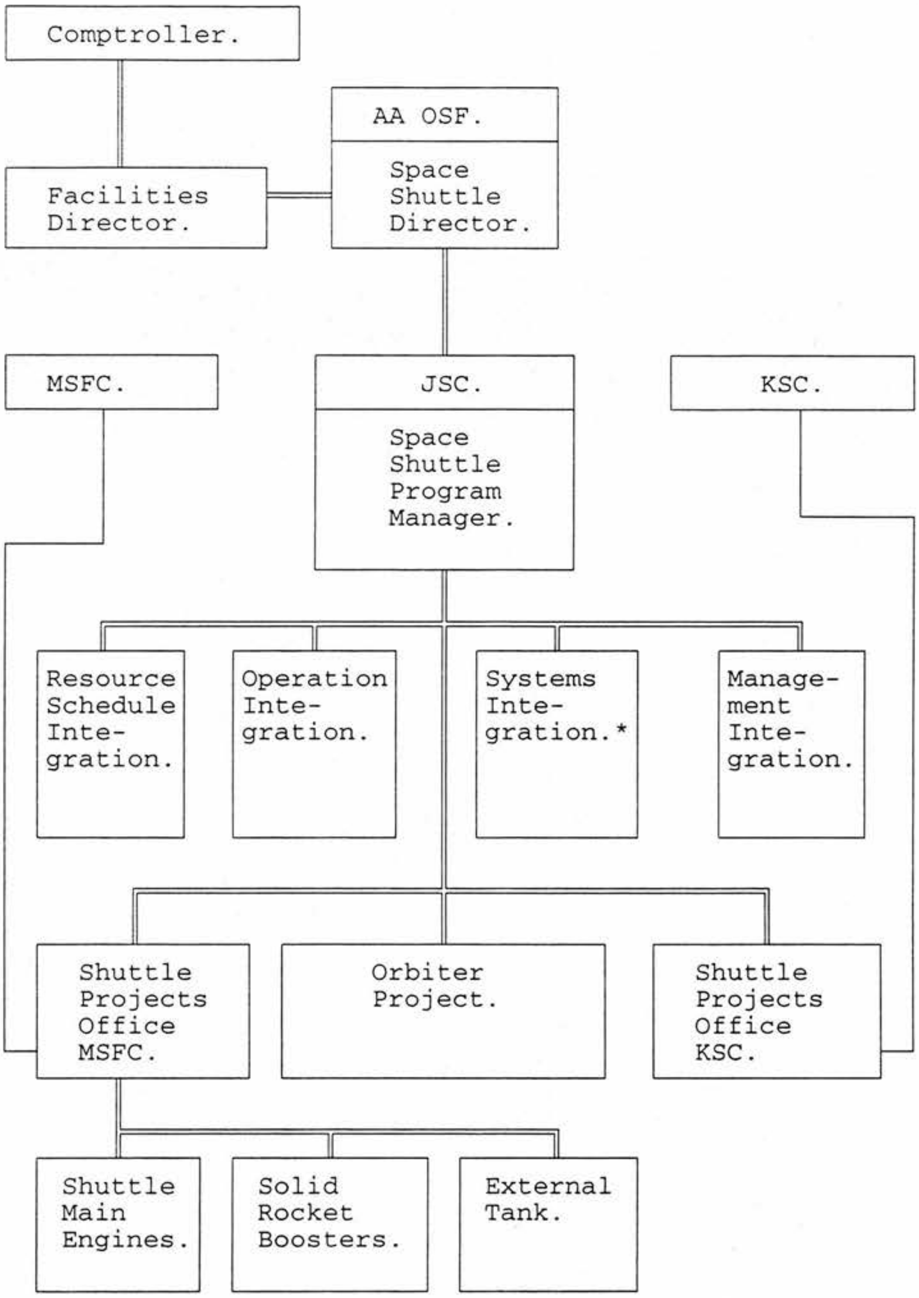


——— Institutional Relationships.

═══ Programmatic Relationships.

* Staffed by JSC, MSFC and KSC.

Table Space Shuttle Management Relationships:1974.



═══ Programmatic Realtionships.

─── Institutional Relationships.

* Staffed by JSC, MSFC and KSC.

> actually tab me to be the Program Manager. ... I essentially had two lines of responsibility, one an institutional line of responsibility to the director of the JSC and a program line responsibility, either to a program director in Washington or the Associate Administrator for Manned Space Flight in Washington. ... I had three major project offices that reported to me ... one here at the JSC, a second group at Huntsville [Marshall] and a third group at Kennedy.[19]

Some within the Office of Manned Space Flight had qualms about the new management system. Paradoxically, the lead Center approach had potential to increase conflict between the various Centers because once it had been established it changed the roles between Johnson, Marshall and Kennedy significantly.[20] The lead Center approached assured Johnson a future in the shuttle programme, but both Marshall and Kennedy remained uncertain about their respective roles. It seemed evident to Marshall that White House and Congressional manoeuvres would force major organizational changes to NASA and Marshall had been declining in the agency pecking order since its director, Dr Wernher von Braun had been transferred to Washington.[21] The subsidence of the two-stage, fully-reusable shuttle in 1971 also troubled Marshall. Elimination of the human-piloted booster, which Marshall hoped to build, resulted in

19 ***Ibid.***

20 ***Ibid.***

21 Arthur Hill, 'MSC Seeks Major Role In Control of the Space Shuttle,' ***Houston Chronical*** (May 9, 1971), p 6.

the programme focused fully on the orbiter.[22] Justifications for the continued existence of the Center, thus appeared weak and Marshall put up a great deal of resistance to the lead Center approach.

> It took a lot of cajoling, so to speak, to get the Marshall Space Flight Center to abide by this lead Center, ... but nevertheless, it was agreed to reluctantly by Marshall.[23]

An equally important, but more subtle undercurrent, dictating a movement towards the lead Center design was its appeal as a device to most effectively utilize NASA's dwindling resources. Although NASA's early accomplishments had become synonymous with outstanding performance and it was 'fashionable to judge other government programs by space agency standards'[24], NASA was not immune from the effects of a steady slow down in productivity growth afflicting the US economy. Stimulated by the massive absorption of scientists and engineers into the vast public works of space and defence, the escalation of the Vietnam War, increased competition with the new economies of Germany and Japan and a balance of payments deficit, government procurement fell across the board. As a result, employment in the fields of space and defence dropped dramatically. Between 1968 and 1972 the aerospace industry witnessed a fall from 1 108 300 employees to 591 400 and

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22 LeRoy Day, letter to the author, May 5, 1996.

23 Christopher Kraft, interview with the author, September 1, 1995.

24 McCurdy Howard. ***Inside NASA.*** p 2.

the number of active industry subcontractors decreased from 6 000 to under 4 000.[25] NASA also suffered a total decline in its employment. Peaking at 400 000 in 1966 it had plummeted to 137 000 by 1971 (see Table 5:1).

The decline in NASA's employment was not only restricted to the rationalization of its contractor support, although this had been reduced by over '2 600 man-years' during 1970.[26] Civil service and direct paid employment at NASA was also undergoing a steady decline (see Table 5:2). A reduction of 425 civil service positions at Marshall, Johnson and Kennedy was made during 1971 and Dale Myers testified to Congress that civil service employment for the three Centers would be further reduced by 600 positions by June 30, 1972.[27]

> I oversaw the down-sizing of the [Kennedy Space Center] ... my primary involvement during those years was trying to retain the skills that we needed to do the rudimentary development of the space shuttle program. ... The philosophy had always been ... that the ... NASA workforce would be the continuing thread and the fabric of the space program, and we used the contractor workforce as the surge tank.[28]

Kennedy, though, had a more immediate problem. Nineteen seventy witnessed the emergence of a debate, which

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25 Mary Kaldor, ***The Baroque Arsenal*** (London, Abacus, 1983), pp 144, 160-4.

26 ***1972 NASA Authorization.*** p 141.

27 Statement by Dale Myers. ***Ibid.***

28 George English, interview with the author, July 26, 1995.

Table 5:1.

Estimate of NASA and NASA Contractor Employment in Selected Areas.

Location.	Peak Year.	Employment Number.	1971	Percentage Decrease.
Kennedy Space Center.	1968	25 700	15 000	41.6
Johnson Space Center.	1968	12 800	10 000	15.6
Marshall Space Center.	1964	23 000	10 100	56.6
Total Space Related Employment.	1966	400 000	137 000	65.7

Source: Adapted from Table 11-2 in Mary Holman, ***The Political Economy of The Space Program*** p 355.

Table 5:2

Paid Employment[a] by NASA Installation: Number on Board at End of FY.

Installation.	1958	1960	1962	1964	1966	1968[b]	1970	1971
Headquarters.	274	662	1 693	2 026	2 274	2 310	2 259	1 939
JSC.	----	----	2 392	4 721	4 688	4 956	4 539	4 298
MSFC.	----	5 367	6 844	7 639	7 432	6 935	6 325	6 060
KSC	----	----	604	1 880	2 618	3 044	2 895	2 704
Total Paid Employees at NASA.[c]	8 420	16 042	25 667	33 108	34 366	34 641	32 548	30 506

a Permanent employees and temporary employees combined, excluding military personnel detailed to NASA.
b Employment figures represent number during middle of year.
c Includes total paid employment of all NASA field centers and offices.

Source: Adapted from Table 3-8, Jane Van Nimmen, Leonard Bruno, Robert Rosholt, ***NASA Historical Data Book Volume 1: NASA Resources 1958-1968*** (Washington DC, NASA Scientific and Technical Information Division, 1988), pp 84-85; and Table 3-8, Ihor Gawdiak, Helen Fedor, ***NASA Historical Data Book Volume 4: NASA Resources 1969-1978*** (Washington DC, NASA History Office, 1994), p 76.

threatened the position of the Center during the operational era of the shuttle.

Uncertainty Over a Launch Site.

Kennedy had served as NASA's launch site since the beginning of the human space flight programme. Located along the Florida coast at Cape Canaveral, Kennedy had grown out of a missile testing range established in 1947. As the Cold War intensified the site rapidly expanded its complex of launch pads (affectionately known as "ICBM Row"), which eventually came to dominate the Cape skyline by the late 1950s. When the Cold War moved into space, NASA became the major player at the Cape. Merritt Island was annexed by the organization in 1961 and the construction of facilities to support the giant Saturn moon rockets soon dwarfed anything that had stood there before.[29] But despite its established history, Kennedy was not automatically viewed as the best location for shuttle operations. During the shuttle's preliminary design and planning phases there was a growing opinion, both within and outside of NASA, that the shuttle's launch and turnaround operations should be conducted from another site.[30] Support technology for

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29 For a detailed history of the Kennedy Space Center see, Charles Benson, William Barnaby Faherty, ***Moonport: A History of Apollo Launch Facilities and Operations,*** (Washington DC, NASA, Scientific and Technical Information Office, SP-4204, 1978).

30 George English. interview with the author, July 26, 1995.

the shuttle was expected to be distinctly different from what was required for expendable rockets.

> Originally, it was hoped that Apollo equipment could be modified at reasonable cost for use on the Shuttle Program. The current studies show that modifications may be so extensive that the effect will be new equipment.[31]

A growing consensus thus formed around the idea of building a new launch site rather than converting Kennedy. By the end of 1970 several studies were under way to identify alternative locations. The two Phase-B contractors, McDonnell Douglas and North American Rockwell, were instructed to 'conduct an evaluation to determine the relative merits of various operations sites.'[32] NASA also established a Space Shuttle Facilities Group consisting of representatives from several program offices, the 'manned space flight Centers', and the Air Force, to be responsible for the development of a 'master facilities plan.'[33] In addition a contract was let out to the Ralph Parsons Company to support the Shuttle Facilities Group in their studies and provide an independent evaluation.[34]

The Office of Manned Space Flight had directed Kennedy to work on a definition of its role in the shuttle

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31 Notes from an operation splinter meeting at the Johnson Space Center, April 27, 1971 (Kennedy Space Center Archives, Florida).

32 Letter from George Low to Senator Clinton Anderson, October 23, 1970 (NASA History Office Archive, Washington DC).

33 Letter from George Low to Representative Olin Teague, December 22, 1970 (NASA History Office Archive, Washington DC).

34 *Ibid.*

programme during a Management Council Meeting in October 1970.[35] Kennedy's appeal to the Office of Manned Space Flight was that NASA should 'take full advantage' of its experience on prior programmes and make effective use of existing resources.[36] It was a strong lobby for the shuttle to be located at Kennedy and a formed the basis of the Center's rationale for holding onto the shuttle's launch, landing and turnaround operations.[37]

Despite Kennedy's defences, over 150 potential locations were examined by NASA. As the launch site studies progressed members of Congress solicited NASA to locate the shuttle's launch and landing site in their state. Senator Clinton Anderson 'insisted that the Shuttle would be in trouble unless it were launched from White Sands Missile Range in New Mexico.'[38] Representative George Miller mobilized the Californians to press for Vandenberg or Edwards Air Force Base as possible locations.[39] NASA also received petitions from Senators Roman Hruska and Carl Curtis for the midwest state Nebraska,[40] and Representative

35 Letter from Kurt Debus to Dale Myers, October 13, 1970 (Kennedy Space Center Archive, Florida).

36 ***Ibid.***

37 George English. interview with the author, July 26, 1995.

38 Ken Hechler, ***Towards the Endless Frontier*** p 287.

39 ***Ibid.***

40 Letter from George Low to Senator Roman Hruska, February 19, 1971 (NASA History Office Archive, Washington DC).

George Mahon for Lubbock, Texas.[41] Senator Edward Gurney and Representatives Lewis Frey, Don Fuqua and Paul Rogers urged that NASA should not move from their home state, Florida, and keep shuttle operations at Kennedy.[42] Representative Olin Teague, although a delegate for Texas, also pushed for Kennedy, telling George Low:

> Unless I am convinced that NASA is making maximum use of existing facilities, I intend to oppose any money for the Shuttle in every way, form or fashion ... it is not "pork barrel" as far as I am concerned.[43]

An eventual change in the shuttle's configuration to gain vital political approval, imposed a very tangible constraint on launch site options. The perceived advantage of NASA's original two-stage shuttle design was that it could be launched from any location. Coastal launch sites, essential for expendable vehicles because of the need for a vast ocean area to safely drop the various rocket stages, would not be a requisite for a system that was fully-reusable. Inland sites had, for the first time, become a real possibility. With the introduction of unguided recoverable solid rocket boosters and the possible emergency jettisoning of the very large liquid hydrogen/oxygen external tank, a vast uninhabited area once

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41 Letter from George Low to Representative George Mahon, May 11, 1971 (NASA History Office Archive, Washington DC).

42 Letter from George Low to Senator Edward Gurney, March 15, 1971 (NASA History Office Archive, Washington DC); Letter from George Low to Representative Paul Rogers, April 1, 1971 (NASA History Office Archive, Washington DC).

43 Olin Teauge, quoted in Ken Hechler, ***Towards the Endless Frontier*** p 288.

again became an integral part of the launch site decision. Members at Kennedy seized this opportunity and pressed the Office of Manned Space Flight for a decision.

> I urge that we make every effort toward an early decision on launch site selections. Because of the inter-reaction between the shuttle design and the geography of the launch site.[44]

With the new configuration launch site locations were narrowed down to three possibilities: Kennedy, Vandenberg Air Force Base (Vandenberg), which had been built to launch the ill-fated Dyna-Soar, and an area in Matagorda County, Texas. As the change to shuttle's configuration also reflected funding restrictions, the investment of over $300 million to construct and equip a new launch site (more than the cost of achieving the same capability at the two existing sites, Kennedy and Vandenburg), also figured high on NASA's agenda. In addition, locating a shuttle launch and landing operation of the dimensions needed for the shuttle at an undeveloped geographical area such as Matagorda County, would require further federal funding to provide community services such as water, sewage, schools, highways and hospitals etc. Kennedy and Vandenberg, it was shown, could jointly serve the national launch requirements and already had the capability to meet all such future needs.[45]

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44 *Ibid.*

45 Major General R.C. Henry, Major General B. Sloan, 'The Space Shuttle and Vandenberg Air Force Base,' ***Air Force Review*** (September/October, 1976), pp 20-26.

In April 1972, NASA decided that both Kennedy and Vandenburg would be the most prudent choices for shuttle operations. Kennedy, situated on the south east coast, would be utilized for all research and development launches and for all easterly operational launches. Vandenberg, situated on the north west coast, was planned to be functional by the early 1980s and would be used for all missions requiring high inclination launches not feasible from Kennedy, including polar orbits.[46] Kennedy was assigned the prime responsibility for the design, development, fabrication, and installation of all ground support equipment to be used at both launch site. The development Centers (Johnson and Marshall) would have the prime responsibility for the variations and additions to this ground support equipment or unique equipment that may be required for shuttle testing at other locations.[47]

Selection of the Principal Contractors.

Once NASA had received Congressional sanction, plans for the procurement of the shuttle's major contracts were put into action very quickly. The approach was to phase the awards to 'allow some certainty to be placed into the

46 Letter from John Foster to James Fletcher, April 13, 1972 (NASA History Office Archive, Washington DC)

47 Memorandum of agreement, space shuttle program ground support equipment responsibilities, May 9, 1972 (Kennedy Space Center Archive, Florida).

weight estimates, operational characteristics'[48] and configurational dimensions of the technological systems. Two awards had thus been secured by mid-1972: the prime contract and the contract for shuttle's main rocket engines. The contract for the shuttle's main engines had originally been procured in July 1971, six months before the presidential announcement to proceed with the shuttle programme.

During the various phases of the shuttle's design competition the overall configuration contractors were not involved in designing the main engines. Instead three contractors, (Aerojet Liquid Rocket Company, a division of Aerojet General Corporation; Rocketdyne, a division of North American Rockwell; and Pratt and Whitney Aircraft, a division of United Aircraft Corporation) had been selected in late 1969 to participate in the Phase-A main engine studies.[49] By June 1971 all three contractors had their engine proposals ready for evaluation. NASA's tight specifications had resulted in three very similar engine designs being put forward. Nonetheless, each of the contractors had subtle differences in their approaches. All of the contractors had tailored their designs to have a sea level thrust range of between 400 000 and 600 000 pounds,

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48 Charles Donlan. interview with the author, June 7, 1995.

49 The original contract was for the development and delivery of 36 main engines for NASA's then two stage fully reusable shuttle. NASA, 'Official Contractor Selection Statement,' reprinted in ***Congressional Record - Extensions of Remarks*** (October 12, 1971), p E10689; 'Reusable Space Shuttle Effort Gains Momentum' ***Aviation Week and Space Technology*** (October 27, 1969), pp 22-24.

reflecting the upward movement in NASA's thrust specification as the shuttle grew in size.[50] The three contractors had also employed the use of a common power-head that could be fitted with a nozzle optimized for either a booster expansion ratio or an orbiter expansion ratio.[51] Where the designs diverged was in the areas of cooling systems and pre-burner structures. Pratt & Whitney chose to incorporate only a single pre-burner in their design because of its potential advantage in reducing the number of failure modes. In addition they selected a path of transpiration cooling instead of the conventional regenerative cooling of the thrust chamber,[52] which, they claimed, would offered better specific impulse figures.[53] In contrast Rocketdyne and Aerojet opted for a traditional regenerative cooling system and utilized two separate pre-burners to drive the fuel and the oxidizer turbo-pumps. The development risk of manufacturing valves for directing the hot gases from one common pre-burner to the two turbo-pumps

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50 By June 1971 the sea level thrust specification had grown from its original 400 000 pounds to 550 000 pounds.

51 Michael Yaffee, 'P&W Shuttle Engine Based on XLR129' ***Aviation Week and Space Technology*** (June 14, 1971), p 52.

52 Regenerative cooling systems date back to James Wyld, who demonstrated such an engine in 1933 for Reaction Motors Inc. The German V2 rocket also utilized the concept and Wernher von Braun incorporated it on the Saturn engines during NASA's Apollo programme. The system comprises of a jacket around the combustion chamber and nozzle through which one of the propellants (on the Saturn engine it was liquid oxygen) is pumped through passages in the jacket to keep the combustion chamber walls cool. The heat absorbed by the coolant is ultimately injected back into the chamber. Transpirational cooling is accomplished by layering a film of coolant along the surface of the combustion chamber and nozzle. Disruptions in the film are renewed by injecting more coolant to reform the film. The process can be abetted by the use of porous materials for the combustion chamber and nozzle walls, so that the coolant injection remains continuous. Adelbert Tischler, letters to the author, March 18, 1997 and June 16, 1997; Mike Gray, ***Angle of Attack: Harrison Storm and the Race to the Moon*** (New York, London, W.W. Norton & Company, 1992), p 84.

53 Michael Yaffee, 'P&W Shuttle Engine Based on XLR129' ***Aviation Week and Space Technology*** (June 14, 1971), p 52.

was a major factor in Rocketdyne's choice of dual units. Separate pre-burners, it argued, allowed them to tailor the pressures differently, which gave better control over the power input into each turbo-pump and meant that each turbo-pump could be trimmed for maximum efficiency.[54]

NASA's eventual selection of a contractor would thus, in part, shape the ultimate design. NASA's initial plan was to select two contractors for the early part of the development phase, but as funding restrictions became more apparent it was decided that just one contract would be awarded. Political pressure was also being placed on NASA as the effects of rising unemployment in the aerospace industry began to bite hard on some states.[55]

Pratt & Whitney's engineers believed that they had the edge over Rocketdyne and Aerojet because of extensive work on their reusable XLR-129 staged combustion rocket engine, which provided much of the technology base NASA used to establish its design requirements.[56] After a short period of deliberation however, and 'to the surprise of many'[57] Rocketdyne received the cost-plus-award-fee contract, worth

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54 William Hieronymus, '$1 billion Shuttle Engine Program Seen' ***Aviation Week and Space Technology*** (June 21, 1971), pp 60-63.

55 Representative Barry Goldwater Jr lobbied James Fletcher during the proposal period supporting Rocketdyne's bid. His motivation arose from a desire to reduce the high unemployment figures in the aerospace community in southern California. Letter from James Fletcher to Representative Barry Goldwater Jr, May 20, 1971 (NASA History Office Archive, Washington DC).

56 Michael Yaffee, 'Reusable Rocket Motor Unveiled' ***Aviation Week and Space Technology*** (August 31, 1970) pp 38-44; Michael Yaffee, 'P&W Shuttle Engine Based on XLR129' ***Aviation Week and Space Technology*** (June 14, 1971) pp 51-57.

57 Jerry Grey. ***Enterprise*** p 107.

over $500 million, in July 1971.[58] Pratt & Whitney immediately filed a petition of protest with the General Accounting Office claiming the award to be unduly biased against them. Rocketdyne, Pratt & Whitney contended, had disregarded the objectives stated in NASA's request for proposals and NASA had failed to conduct proper written or oral discussions. The substantive basis for Pratt & Whitney's protest was that they had already built and tested a staged combustion engine, which met most of NASA's specifications. Rocketdyne, on the other hand, had never run a complete staged combustion engine. Consequently, Pratt & Whitney believed their proposal to be technically superior and thus did not understand the basis for NASA choosing Rocketdyne over themselves.[59]

While Pratt & Whitney's engine proposal had won on management and work approach criteria, NASA's Shuttle Engine Evaluation Board considered that Rocketdyne's engine proposal surpassed Pratt & Whitney's in a number of areas, namely: a better vehicle and engine integration design; an interface design that was more compatible with NASA requirements; the use of an established regenerative cooling design, which was thought to be superior over Pratt & Whitney's transpiration cooling approach; and finally

58 NASA. 'Official Contractor Selection Statement', reprinted in ***Congressional Record - Extensions of Remarks*** (October 12, 1971) p E10689; 'Shuttle Engine Awarded to Rocketdyne' ***Aviation Week and Space Technology*** (July 19, 1971) p 12.

59 Jerry Grey, ***Enterprise*** p 110; 'Pratt and Whitney Protest Shuttle Engine Award' ***Aviation week and Space Technology*** (August 9, 1971), p 23.

Rocketdyne presented their proposal at a lower cost. Pratt & Whitney's design was also considered to be weak in defining ground support equipment and although they had demonstrated the XLR-129 in test, unlike Rocketdyne, Pratt and Whitney did not have a proven flight record with the size of engine demanded by the shuttle.[60]

> One engine on the old Apollo stack was not Rocketdyne's. All the rest were Rocketdyne engines. A company with all that background and certainly the leading rocket engine company, was competing against Pratt and Whitney. Their engine was ... nowhere near the size engine that was being called for ... and Rocketdyne's F-1 engine at the bottom of the of the Saturn V stack was a big mamma. ... Rocketdyne had an immense design and experience over Pratt and Whitney.[61]

NASA's underlying rationale for choosing Rocketdyne however, can also been seen as the result of an interplay between technological matters and entrenched social relations. Marshall, who had management responsibility for the shuttle's main engines, had a long and well established relationship with Rocketdyne, as Rockwell's (Rocketdyne's parent company) Space Shuttle Manager, Bastian Hello disclosed:

> For Rocketdyne to win was almost a given. [Pratt and Whitney's] experience was with the Air Force it wasn't with Marshall. Marshall had Rocketdyne people in their compound, in there every day doing business with them and their going to go and pick an Air Force contractor, not likely.[62]

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60 NASA, 'Official Contractor Selection Statement', reprinted in ***Congressional Record - Extensions of Remarks*** (October 12, 1971).

61 Bastian Hello. interview with the author, April 27, 1995.

62 Bastian Hello. interview with the author, April 27, 1995.

Agreement with Marshall's decision to stay with the company they knew did not find universal consensus within NASA.

> The contractor that had done the work on the Saturn engines was accepted by the MSFC as confident to do this work on the shuttle but, ... frankly they weren't up to it.[63]

Given the protest, NASA agreed not to 'award the definitive contract' for the development of the shuttle's main engines until the General Accounting Office had acted.[64] Nonetheless, NASA continued to use Rocketdyne in the design and planning of the engine under an interim contractual arrangement until March 1972 when the protest was finally settled in Rocketdyne's favour.[65]

NASA's selection of Rocketdyne in 1971 had a big effect on the rest of North American Rockwell, who were still putting their bid together for the orbiter, as Rockwell's Space Shuttle Manager, Bastian Hello recalled:

> When a division of our company was awarded the rocket program [our] first reaction was, well that's it we have no chance of winning the orbiter. That's our piece of the action and one of the biggest fights I had was keeping the pressure on.[66]

Four companies (Grumman Aerospace, Lockheed, McDonnell Douglas Corporation and North American Rockwell) submitted bids for the shuttle's prime contract. Two months were

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63 Adelbert Tischler. interview with the author, May 3, 1995.

64 Letter from George Low to Senator Allen Ellender (August 11, 1971).

65 Dennis Jenkins. ***Space Shuttle*** p 122.

66 Bastian Hello. interview with the author, April 27, 1995.

allocated for the preparation of proposals, with a further two months designated for NASA to analyze them. Negotiations between NASA's Source Evaluation Board and the contractors hence began on July 1 1972. The shuttle's request for proposal were described as the 'loosest procurement document ever issued by the NASA for a major program.'[67] Emphasis was being placed on innovation around a basic concept, revealing NASA's intention to keep the design details relatively fluid, allowing for the possibility of using elements from each of the contractors in the final configuration.[68]

Politically each of the contractors had both internal supporters and adversaries within NASA, but all had allegiances with certain areas.

> All the areas of Johnson had their favourites. There was those who had worked with Grumman on the Lunar lander and there were those who had worked on the command service module and they were all for [Rockwell]. And there were those that couldn't stand either one of the two, wanted someone else, wanted a change and ... thought that it was time to take a major piece of the business away from [Rockwell] ... and give it to another contractor.[69]

During the evaluation North American Rockwell and Grumman scored very high and were extremely close in the final proposal ranking; followed by McDonnell Douglas and then

67 Zack Strickland, 'Space Shuttle RFP Stresses Innovation' ***Aviation Week and Space Technology*** (March 27, 1972), p 18.

68 Charles Donlan. interview with the author, June 7, 1995.

69 Bastian Hello interview with the author, 27 April 1995.

Lockheed. McDonnell Douglas scored badly because the Source Evaluation Board considered that McDonnell Douglas's organization of the eastern and western segments of the company were relatively complex. The recent merger between the two companies resulted in a proposal where engineering functions were divided between both locations. NASA ultimately thought that this would complicate the assignment of overall engineering responsibility.[70] John Yardley, then working for McDonnell Douglas recalled:

> We were struggling with this merger and there was a lot of bad feeling with the Douglas people ... because they thought they were much better at everything, ... but anyhow we finally wrote a proposal that split up the work between Douglas and McDonnell and there was a 2 000 mile gap, so it wasn't a good organizational proposal. .. I went to Washington to talk to Bob Thompson and some of those guys and they said you guys have the best Phase-B proposal but then you give us all this mish mash of an organization that we can't understand.[71]

Although close in the ranking, an unfortunate event at Grumman had left them with a hole in their organizational structure as Grumman engineer Richard Kline remember:

> We started going through our bid then ... Lou Evans died of a heart attack ... [so] Joe Gavin was made president of the company and that then created a management void ... and the up shot of it ... was that in the final evaluation ... we were judged to be sizeably less competitive. ... The Grumman proposal was technically the strongest of the three, but it lost hands down in the management activities, it was also the highest cost. ... We proposed a cost which we

70 NASA's official contractor statement for the space shuttle program, September 1972 (NASA History Office Archive, Washington DC).

71 John Yardley. interview with the author, August 9, 1995.

> thought was low but nevertheless realistic, but it was more than other bidders had proposed who were also technically adequate.[72]

It was North American Rockwell who had submitted the lowest bid at $2.8 billion. This, along with their success with the main engine contract, gave it some cause for concern.

> I can remember the consternation on our chairman's part when he heard that we were the lowest bidder. He thought ... we'd got a big loser on our hands and I hasten to tell him that you've got one of the world's biggest winners on your hands.[73]

In the end though, North American Rockwell's apprehension was unfounded. On July 26, 1972 the Space Transportation Systems Division of North American Rockwell won the $2.6 billion contract to design and build the space shuttle orbiter and manage the systems integration function.

> I recall the word coming in sometime in the month of July that we had won it. Of course there was a huge hip hip hurrah and a lot of gnashing of teeth in the other companies. ... Grumman was particularly upset because ... coming out of Johnson they thought that they had won the technical proposal and it turned out in retrospect that indeed they had. We had won the management and cost proposals and we were close enough in the technical proposal that the odds went over to us.[74]

However, NASA imposed restrictions on North American Rockwell, especially over its choice of sub-contractors.

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72 Richard Kline. interview with the author, May 31, 1995.

73 Bastian Hello interview with the author, 27 April 1995.

74 Bastian Hello interview with the author, 27 April 1995.

> NASA told us that you are going to include the other contractors, you are not going to leave them out in the cold. [However,] while NASA said you will include them they were very reluctant to say give them this and give them that, they pulled back from that. One of the first things that happened past the win and the ... Rockwell euphoria, was the [Rockwell] president and I flew around to see the other contractors. I can recall clearly walking into Joe Gavin's office and ... talking about what piece of the action would they get. ... Grumman had been telling their people ... and their shareholders, not to worry we are going to get a billion dollars of this program. Well that wasn't to be and they were quite let down when they found out .. that their piece of the action was building wing sets.[75]

Integrating the Gargantuan.

Combined with the orbiter contract was a second task, named an integration and support.

> We had already put together an organization that had a nucleus of government people leading all kinds of activities, but we wanted a prime contractor to plug into that integration support activity to help us prepare interface control documents, to help us prepare weight programs, to help us prepare all the interface engineering.[76]

Systems integration had grown more complex with the advent of each new programme. The Mercury and Gemini programmes both had comparatively simple physical and functional interfaces between space craft and launch vehicle. During Apollo, the interfaces, although more complex, were again intentionally kept simple.

> Up until the time that we started with the shuttle, what we did was minimize the interfaces

[75] Bastian Hello. interview with the author, April 27, 1995.

[76] Robert Thompson, interview with the author, September 7, 1995.

> between the manned part of the vehicle and the power part of the vehicle so that there were only several wires. There was very little transfer of information back across the interface between the spacecraft and the rocket and so the coordination and integration problems were insignificant, relatively speaking.[77]

The arrival of the space shuttle, however, marked a significant change in the management of systems engineering and integration. The tenet of shuttle development was to have an integrated vehicle where the most expensive part, the orbiter, was to be recovered and reused. This led to a design concept that placed a great majority of the technological sub-systems, including major proponents of the propulsion systems, inside the orbiter. Accordingly, the interface complexity between the programme's technological elements and the NASA Centers would increase dramatically. It was decided, therefore, to employ the orbiter contractor (the main hardware development programme), in a dual role, by also allowing them to provide integration support.[78] The responsibility of the shuttle's prime contractor was thus reinforced.

> All the different contractors that were involved in building the shuttle had different geographical locations ... posed a considerable challenge. We started off having interfaces at each one of the prime contractor plants ... so the major part of the integration contract was to serve as an interface with all the various contractors to make sure that what they were

77 Christopher Kraft, interview with the author, September 1, 1995.

78 Owen Morris. 'SE&I and Management for Manned Space Programs' Francis Hoban. William Lawbaugh. Ed. ***Readings in Systems Engineering*** (Washington DC, NASA, Scientific and Technical Information Program, 1993) pp 87-104.

> doing, and the lessons they were learning during the design ... all teamed together.[79]

However, as time went on it became clear that Rockwell was unable to organize all the complexity on its own: as Johnson Engineer, Norman Chaffee recalled:

> Initially, [systems integration] was kind of haphazard. ... We had Rockwell as the integrator of systems within the orbiter. They didn't do a particularly [good] job of doing that, but going beyond that, the integration of how does the orbiter fits onto the external tank and how does the solids fit on that, and what are all the integrated loads and how to the main engines fit into the orbiter, how does the fluid system feed everything, ... none of that was very well organized.[80]

Rivalry between the Centers was also causing problems with management surveillance, evaluation of Center activities, systems integration and technical control; as NASA's Associate Administrator, John Yardley, reported in 1974:

> The sister Centers are always suspicious of the objectivity of the lead Center. ... R.L. Thompson ... feels that once the technical direction has been given, it's clearly the other Center's responsibility if problems arise. Chris Kraft ... concluded that [Johnson] could not direct [Marshall] as a practical manner. This problem is further complicated by the fact that the two Centers have entirely different management styles, so that even if the other negative factors could be resolved, this would remain ... a continual source of controversy.[81]

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79 Raymond Dupree, interview with the author, August 8, 1995.

80 Norman Chaffee, interview with the author, September 9, 1995.

81 Memorandum from John Yardley, Associate Administrator for Manned Space Flight to the Deputy Administrator and the Associate Administrator, December 26, 1974 (NASA History Office Archive, Washington DC).

Thus, a systems integration organization was established within the Space Program Managers Office at Johnson, which was defined specifically to report to the overall Program Manager. Under the control of Owen Morris, the organization was responsible solely for integration of various components. An important aspect of its successful governance was a recognition of the existence of separate projects and the diversity under which these projects were being produced. Morris decide, therefore, to ignore issues that arose within the confines of these distinct projects and concentrate only on bringing all the pieces together and making sure that the machine worked as a whole. This was done by each division identifying people within their projects to take on the duties of systems integration, who then reported directly to Owen Morris.[82]

Of course, with a project as large and as complex as the shuttle, politics was an inherent part of the interface. As Johnson Engineer, Norman Chaffee recalled:

> Because of the fact that we were doing the main propulsion feed system in the orbiter we were responsible for all of the components that took the [propellants] from the external tank and feed it to the main engines. Marshall Space Flight Center built the external tank and the main engines, and we were responsible for all the stuff in between ... so there was a very strong interface we had with the MSFC. ... [So] there was always a big flap between Marshall and Johnson having to do with the proper interface values and our ability to either take propellant from them at the right conditions and give it

82 Robert Thompson, interview with the author, September 7, 1995; James Jackson, interview with the author, July 12, 1995; Norman Chaffee, interview with the author, September 9, 1995.

> back to them at the engine at the right conditions; and in order to accommodate a development problem we had, if we needed some relaxation from them they were always very reluctant to give it. They wanted us to solve our problem, didn't want us to create a problem for them; and the same way if they needed some relaxation or some tighting of a specification to solve an engine problem or tank problem then we would be equally reluctant to give any ground (see figure 5:2 for interface).[83]

Solutions to both technical and political problems were often reached through a series of working groups and systems integration groups. These would be jointly chaired by senior managers of the Centers involved and would meet at alternate locations to placate some of the political rivalry. Along with staff from the Centers would attend their contractors. Staff from Rockwell, who still had responsibility for overall integration, and Owen Morris's team would also attend to support these meetings.[84]

> These meetings ... were huge, sometimes [they] would last three or four days and get very contentious and very detailed. Most issues ended up, because at the core engineers are reasonable people and can be rational, most things could be worked out. We could find some rationality, and where it couldn't, is primarily where schedule and money was involved.[85]

If a solution could not be found, or a Project Manager would not sign up for a particular change, then the issue would move up to the Configuration and Control Board, or

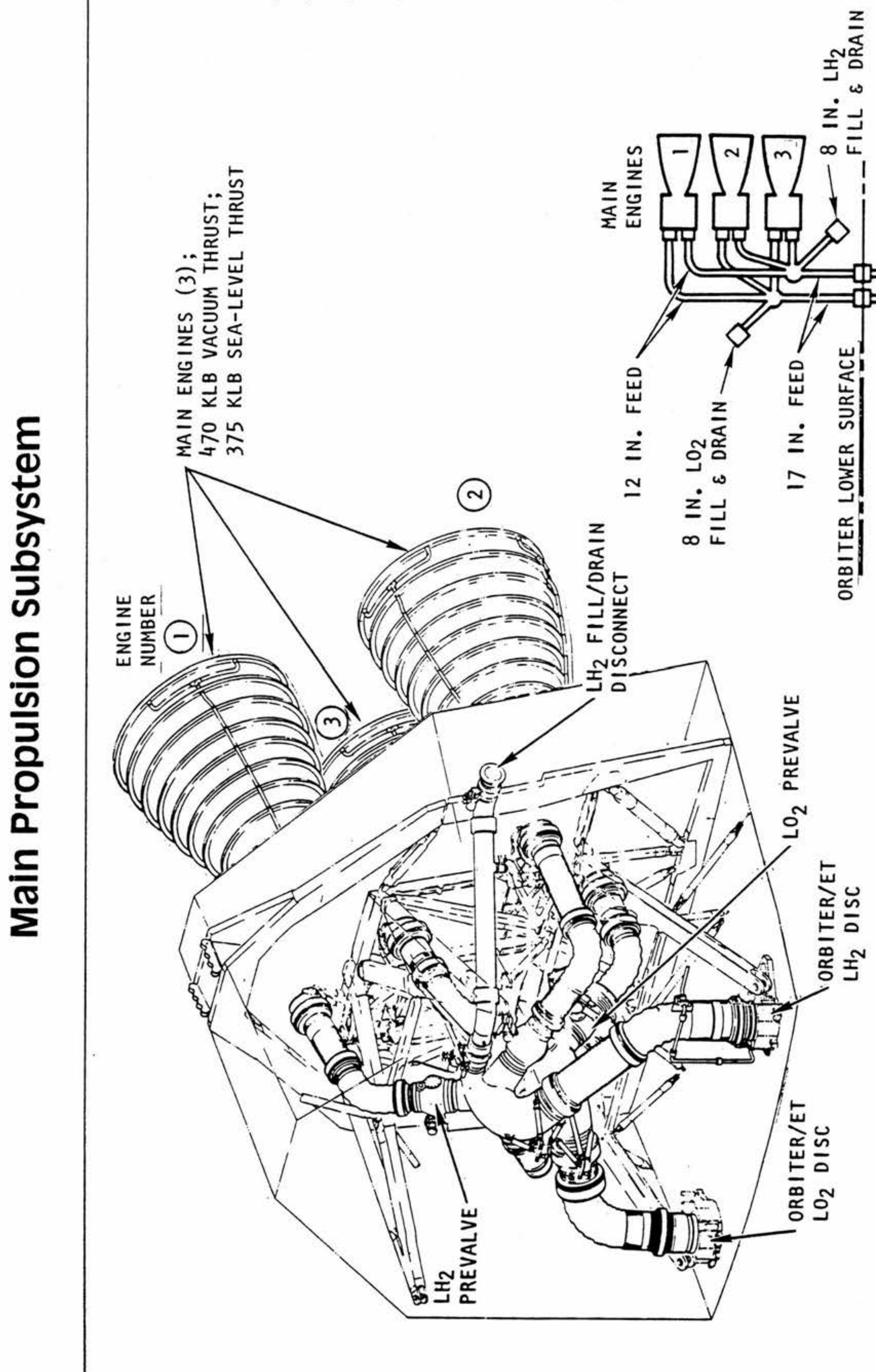
83 Norman Chaffee, interview with the author, September 9, 1995.

84 James Jackson, interview with the author, July 12, 1995; Norman Chaffee, interview with the author, September 9, 1995.

85 Norman Chaffee, interview with the author, September 9, 1995.

Figure 5:2.

Source: W.H. Morita, (ed) ***Space Shuttle System Summary.***



change board, which was chaired by Space Shuttle Manager, Bob Thompson. The integration working groups were held on a weekly basis every Wednesday and the change boards were held every Friday. The motivation behind this timetable was that it was hoped that problems could be worked out in the days in between, so that they did not have to appear before the change board. Nevertheless, there was always plenty of activity within the change boards and one was held every Friday, throughout the programme.[86]

In the change board, Thompson would sit at the head of a table and around this table would be ten or twelve key advisors. Various systems experts would then come into the meeting a give a presentation on what tests had been done, what recommendations were being made and what changes they wanted to introduce. If the Project Manager was not located at Johnson, then Thompson would also be in teleconference with the Project Manager and usually with other engineers at different locations, to get their input.

> Typically in a bureaucracy like NASA you have lots of different people going off in lots of different directions, studying and analyzing what if we do this, what if we do that. Then you have to have some way to bring all those things into a central form under a Program Manager, and that Program Manager also has to sit there and listen to the various debates ... then decide what to do.[87]

And as Johnson's Director Christopher Kraft recalled:

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86 Robert Thompson, interview with the author, September 7, 1995; James Jackson, interview with the author, July 12, 1995; Norman Chaffee, interview with the author, September 9, 1995.

87 Robert Thompson, interview with the author, September 9, 1995.

> Bob Thompson forced a consensus on every technical issue.[88]

Progress toward the construction of the gargantuan sociotechnical ensemble had now moved on a stage. Points of closure had been reached on design and the mobilization of people and artifacts gained momentum. NASA was poised to activate the ensemble and set it in motion toward its ultimate goal: the construction of the machine. The fusing of both technological and social organization had commenced, driven by a singular purpose: the translation of a concept into an object. The shape and direction of the ensemble however, fed upon reflections from the past as well as a vision of the future. Its burgeoning nature, form and function was thus witnessed with some trepidation in certain quarters of NASA.

> When the shuttle program was approved ... NASA officials and many other people in NASA, plus a great number of the contractors, said this is the Apollo substitute. The Centers rushed to get their people piled onto this program, a drastic mistake because everyone wasn't competent to do that kind of thing. The contractors that were accepted by the Centers were identically the same contractors used in the Apollo program. In many respects ... right there the program was starting to go wrong.[89]

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88 Christopher Kraft, interview with the author, September 1, 1995.

89 Adelbert Tischler, interview with the author, May 3, 1995.

Chapter 6

Political Uncertainty and Financial Crisis

> The machine is not neutral, ... technology is always a historical-social project: in it is projected what a society and its ruling interests intend to do with men and things.[1]

Electorial Divisions.

Despite the increased pace in constructing the gargantuan sociotechnical assemblage, external resistance was still being experienced. The shuttle programme had not moved beyond the point where it could be easily curtailed and there were still powerful opponents in the political arena who were prepared to take up that cause.

1972 was an election year and the award of a multi-billion dollar project during such a volatile period did not go unchallenged. NASA's selection of North American Rockwell sent out minor shock waves, which caused some factional eruptions in Congress. Jean Westwood, Chair of the Democratic National Committee, considered that NASA's preference for North American Rockwell had come from more than just practical considerations. Five directors of North American Rockwell had contributed to Nixon's 1968 election campaign, so Westwood claimed that the Rockwell award

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1 Herbert Marcuse, 'Industrialization and Capitalism in the Works of Max Weber' ***Negations*** (Boston MA: Beacon Press, 1969), pp 225, 224.

represented the 'latest, and perhaps most blatant example of President Nixon's calculated use of the American tax payers dollars for his own re-election purposes.'[2] As such, Westwood pushed for an investigation into the relationship between contributions from directors of North American Rockwell to the presidential election campaign and NASA's award of the shuttle contract to be conducted.[3] North American Rockwell declined to make any comment on the allegations, but NASA was eager to deny that politics played any part in the selection process and stated that North American Rockwell was 'chosen on technical and management merits alone.'[4] Within Congress Westwood received severe criticisms from her fellow Democrats. Representative Olin Teague (Democrat, Texas), claimed the shuttle contract was 'one of the most thoroughly and objective studied contract awards in any recent major government program.'[5] The call for an investigation was seen by others as a political manoeuvre to force ground between Nixon and one of the Democratic candidates, George McGovern, as the presidential election campaign heated up.

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2 Jean Westwood, quoted in 'The Democratic National Committee' ***Aviation Week and Space Technology*** (August 7, 1972), p 15.

3 The five identified by Jean Westwood were: J.L Atwood, contributed $2000; George Karch, $1000; Frederick Larkin Jr, $1000; Henry Mudd, $3000; and Willard Rockwell, $1000 (1972 dollars), ***Ibid.***

4 Zack Strickland, 'Shuttle costs Remain $5 billion' ***Aviation Week and Space Technology*** (July 31, 1972), pp 12-13.

5 Olin Teauge, quoted in 'The Democratic National Committee,' ***Aviation Week and Space Technology*** (August 7, 1972), p 15.

Representative Thomas Downing (Democrat, Virginia) warned against such tactics when he told the House floor:

> I don't know how large a bloc they are, but the ticket might as well write off all the voters who are affected either directly or indirectly by the aerospace industry.[6]

Westwood failed in her attempt to get an investigation, but the shuttle remained a target in the electorial affray.

As in 1968, the continued involvement of the US in Vietnam dominated the 1972 election. Nixon's 'secret plan' to end the war in six months and ensure 'peace with honour' had proven disastrous. The Administration appeared no closer to a solution at the end of their four year term, in spite of their detente and Vietnamization policies.[7] A resolution to Vietnam, therefore, clouded many other issues during the election campaign, including Watergate.

An overwhelming majority in all the Republican primaries ensured Nixon his nomination to stand again.[8] The Democratic primaries had furnished a sufficient majority for Senator George McGovern to stand as Nixon's adversary; a nomination which had surprised many because of McGovern's radical platform. The mainstay of McGovern's manifesto was his proposals for a 'peace economy', which involved: the immediate pull out of US troops from Vietnam; the 'phasing

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6 Thomas Downing, quoted in Ken Hechler, ***Towards the Endless Frontier*** p 290.

7 Stephen Ambrose, ***Rise to Globalism: American Foreign Policy, 1938-1980*** (Middlesex, England, Penguin Books Ltd, Second Revised Edition, 1981), pp 308-334.

8 Richard Nixon, ***The Memoirs of Richard Nixon*** p 544.

down' of military spending and a corresponding increase in government spending on welfare, education, health, housing and other civilian projects; and the tightening up of the tax structure which was perceived as 'only benefiting big business.' For the aerospace industry in particular, McGovern's plan was for conversion. Military production was to be replaced by civilian production.[9] Although NASA was established as a civilian agency and prided itself on its civilian status, McGovern believed the shuttle to be primarily a military programme. Two weeks after Nixon's announcement to develop the shuttle, McGovern told a Florida campaign audience that if elected he 'wouldn't manufacture a foolish project like the Space Shuttle to provide jobs' and that furthermore he considered the programme to be 'an enormous waste of money.'[10] The shuttle had thus become part of the divide between the McGovern and Nixon tickets.

An early campaign speech from Vice President Spiro Agnew also focused on the shuttle as an election issue. Agnew launched a vicious attack on the shuttle's critics labelling them as 'reactionaries, utopians and unrealistic' in arguing that spending on space technology should be redirected to social problems. Such policies he argued, would 'bring to a virtual halt this country's technological

9 George McGovern, ***An American Journey: The Presidential Campaign Speeches of George McGovern*** (New York, Random House, 1974).

10 George McGovern, quoted in Ken Hechler, ***Towards the Endless Frontier*** p 289.

progress.'[11] The advancement of science and technology, the accumulation of new knowledge, spin-off technology and investment in high skilled employment were all well rehearsed compositions of promotional rhetoric for the space programme and Agnew cited them all as examples of the 'benefits from the space program that will improve the quality of life for all mankind.'[12]

On the side of the Nixon campaign was a large portion of the aerospace industry. The shuttle's relationship to jobs in that sector and its embodiment of scientific and technical progress meant that McGovern's intentions received a hostile reaction from many in the business. One of its public voices, *Aviation Week and Space Technology* took a strong stance against McGovern in its editorial at the time:

> His campaign speeches make it clear, that if elected, he intends not only to wipe out the future defense posture of this nation, but also strip its new technology to bare bones.[13]

The diatribe went on to claim that McGovern stood against 'every major aerospace technical development program including the shuttle,' and that his policies would 'wreak havoc upon the US.' In their view, 'for an aerospace worker to vote for Sen. McGovern would be to vote for self-

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11 Spiro Agnew, address by the Vice President of the United States at the Florida Jaycees State Convention, Daytona Beach, Florida, January 29, 1972 (Kennedy Space Center Archive, Florida), pp 1,2.

12 ***Ibid.*** pp 5,6.

13 R. Hotz, 'Editorial,' ***Aviation Week and Space Technology*** (July 31, 1972), p 7.

destruction'.[14] Much the same conclusion had also been drawn within the higher echelons of the aerospace unions. The American Federation of Labour and the Congress of Industrial Organizations (AFL-CIO) were so vexed by McGovern's nomination that for the first time in its history the executive council adjourned without voting for any presidential endorsement.[15]

The AFL-CIO's declaration of neutrality however, did not prevent considerable labour support for McGovern, even among central labour bodies constitutionally subject to official policy.[16] Delegates to the 1972 International Association of Machinists and Aerospace Workers (IAM) convention voted to endorse McGovern despite a resolution urging the IAM to remain neutral because of McGovern's opposition to the Super-Sonic Transport programme, the Lockheed loan and the B-1 bomber.[17] Nixon though, found no support among the IAM delegates. IAM President, Floyd Smith, emphasized Nixon's poor record, especially in the aerospace industry, in his keynote speech:

> By ordering deep cutbacks in defense spending, government employment and space expenditures and

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14 *Ibid.*

15 Conservative politics prevailed within the AFL-CIO executive long after Vietnam had shattered the cold war consensus. Although its middle class allies had deserted Johnson and campaigned for an end to the war the AFL-CIO continued to support the conflict. To the AFL-CIO, McGovern's nomination was a manifestation of what they perceived as an extremist take over of the Democratic Party. David Brody, ***Workers in Industrial America: Essays on the Twentieth Century Struggle*** (New York, Oxford, Oxford University Press, 1980), pp 238-244.

16 *Ibid.* p 242.

17 'Convention Backs McGovern, No Support at all for Nixon' ***The Machinist*** (September 14, 1972), pp 1,7.

> offering no proposals for conversion to meet the peacetime needs of the nation, the Nixon Administration increased the number of depressed areas from six in early 1969 to 62 by early 1972. The nation's aerospace Centers were especially hard hit. Hundreds of thousands of workers in all job classifications were stranded in communities which had no use for their skills. ... When Congress tried to provide such an alternative by appropriating funds to create needed jobs ... Nixon either vetoed these efforts or refused to release funds that had already been authorized.[18]

Nevertheless, Nixon had the support of his "silent majority". A Gallup poll at the end of August put Nixon in the lead with a 64 percent share of the vote and had McGovern trailing behind with only 30 per cent.[19] Kissinger's secret talks in Vietnam with Le Duc Tho had almost reached a point of agreement, inspiring Kissinger to announce on October 26, just in time for the election, that 'peace is at hand.' Despite McGovern's plea to the electorate, to not 'let this man fool you again', 60 per cent of the voters chose Nixon in the largest victory in modern American electorial history.[20]

Although Nixon's Administration could not be described as ardent champions of the human space programme, a Republican triumph assured relatively strong support for NASA's shuttle programme. Presumably, given McGovern's rhetoric, the shuttle would have been a symbolic peace economy victim. Even assuming that McGovern could not have

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18 Floyd Smith, quoted in ***Ibid.*** p 7.

19 Richard Nixon, ***The Memoirs of Richard Nixon*** p 680.

20 Stephen Ambrose, ***Rise to Globalism*** pp 333-334.

forced through all of his radical policies, it is conceivable that a Democrat win would have resulted in the programme's immediate cancellation.

Shoots of Financial Crisis.

Throughout the election year the Office of Management and Budget indicated to NASA that it was in full accord with the settlement over the shuttle.[21] But the shuttle did not represent the totality of NASA. The agency's resources were spread over a myriad of different programmes, both operational and in the making. Hence, for NASA, an important part of the 1972 settlement entailed a commitment to retain the agency's total annual funding; as NASA Administrator, James Fletcher, advised Nixon in July 1973.

> In January 1972 when you approved the space shuttle development, I stated that I could conduct the right kind of space program ... at a "constant budget" [sic] of $3.4 billion. ... I would have not recommended starting the shuttle at a lower budget projection.[22]

NASA's interpretation of a *constant budget*, was a guaranteed annual funding level $3.4 billion, in FY 1971 dollars, during the shuttle's development. Such a rigid interpretation was not, however, shared by the Office of Management and Budget. Fletcher's request for a $1 billion

21 Memorandum from Willis Shapely to George Low, July 26, 1972 (NASA History Office Archive, Washington DC); Letter from James Fletcher to Roy Ash, Director of the Office of Management and Budget, July 13, 1973 (NASA History Office Archive, Washington DC); Letter from James Fletcher to Richard Nixon, July 13, 1973 (NASA History Office Archive, Washington DC).

22 Letter from James Fletcher to Richard Nixon, July 13, 1973 (NASA History Office Archive, Washington DC).

shuttle reserve was immediately cut and NASA's FY 1973 budget was submitted in 1973 dollars so NASA lost any inflationary increments.[23]

In the months following Nixon's reelection the Office of Management and Budget formulated plans to curb the growth in federal spending. Having permitted heavy spending in 1972, in part to assure a Nixon victory, the Office of Management and Budget intended to reverse policy and work towards what they regarded as desirable economic goals: a reduction of the budget deficit to $12.7 billion in FY 1974 and a programme of more austere economies for the following years to reduce it further.[24] In December 1972, NASA was told by the Office of Management and Budget that it had to take a major cut in its FY 1974 funding as part of the overall budgetary squeeze.[25] The result was a presidential budget request for NASA in FY 1974 of just over $3 billion.[26] As projections for FY 1975 did not appear to offer any alleviation, Fletcher advised Nixon of a pending crisis.

> It will not be possible to continue to run a balanced program ... unless adequate funding is provided in FY 1975 and in future years. ... We

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23 Robert Thompson. interview with the author, September 7, 1995; NASA's total appropriation for FY 1973 was $3 407 636 000. Ihor Gawdiak, Helen Fedor, ***NASA Historical Data Book Volume IV*** Table: 4-12, p 133.

24 James Reichley, ***Conservatives in an Age of Change*** p 227.

25 Letter from James Fletcher to Roy Ash, Director of OMB, July 13, 1973 (NASA History Office Archive, Washington DC); Letter from James Fletcher to Richard Nixon, July 13, 1973 (NASA History Office Archive, Washington DC); Joseph Trento, ***Prescription for Disaster*** pp 129-130.

26 Ihor Gawdiak, Helen Fedor, ***NASA Historical Data Book Volume IV*** Table: 4-13, p 134. NASA's total appropriation for FY 1974 stood at $3 039 700 000.

> ... assumed (with Office of Management and Budget knowledge) that the reductions were only temporary, and that future years' budgets would again reach the required level. The programs we now have under way cannot be sustained at the FY 1973/74 levels, nor can they be sustained at the Office of Management and Budget projected level of $3.2 billion for FY 1975. ... Either the shuttle will have to be cancelled and with it the only future plans for US men in space, or we will have to forgo one or more of the major areas of output.[27]

Despite NASA's supplications, the agency's total FY 1975 budget only just exceeded $3.2 billion.[28]

The combination of sustained funding cuts and emergent cost-overrun from some of the shuttle contractors were, by themselves, major contributors to the onset of financial difficulties at NASA. With the fusion of a larger, more pervasive, ingredient, inflationary crisis, NASA's financial difficulties only got worse.

The seeds of inflationary crisis had been sown long before NASA embarked upon the shuttle programme. Sustained economic growth in the US had been based primarily on an increasing reliance on the cheap flow of oil and raw materials from the Third World. Oil had become an important raw material for all the advance capitalist countries. The proportion of oil in the world energy supply had increased from 21.5 per cent in 1940 to 67.2 per cent in 1974. The price of raw materials including oil had not risen much in

27 Letter from James Fletcher to Richard Nixon, July 13, 1973 (NASA History Office Archive, Washington DC).

28 Ihor Gawdiak, Helen Fedor, ***NASA Historical Data Book Volume IV*** Table: 4-14, p 135. NASA's total appropriation for FY 1975 stood at $3 231 093 000.

more than twenty years and the US had benefited from favourable terms of trade with the Third World that had remained low during the 1950s and 1960s. Tired of capitalist exploitation, a general movement in the Third World sought to redress the balance and force through more equitable terms of trade. The prices of corn and timber rose first, followed by textiles and finally, in the autumn of 1973, the Organisation of Petroleum Exporting Countries, described as powerless in the ten years after its foundation in 1960, quadrupled the price of crude oil. Terms of trade had already risen by 13 per cent in 1970-73, with the oil shock they rose a further 69 per cent in 1970-74. The prices of raw materials almost doubled over about a year from the summer of 1972 until the autumn of 1973, prior to the oil shock. The rising prices of primary products, together with rising wages, squeezed US profit rates substantially; and although real wages became sluggish in 1973 and actually fell in 1974, the profit rate plummeted with an outbreak of inflationary crisis.[29]

Prodded by rising prices, falling wages and massive lay-offs, organized labour in the major aerospace industries went into negotiations, demanding both substantial flat wage increases and changes in the formulas for calculating cost-of-living clauses. The initial

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29 Itoh Makoto, ***The World Crisis and Japanese Capitalism*** (London, MacMillan Press, 1990), pp 32-34, 50-57; Eric Hobsbawm, ***The Age of Extremes: The Short Twentieth Century 1914-91*** (London, Michael Joseph Ltd, 1994), chapter 9.

response by management at the large aerospace companies, Boeing, Lockheed, McDonnell Douglas and Rockwell, was to consistently reject proposals put forward by unions and refuse to negotiate. By the end of 1974, however, Boeing and Lockheed had entered into an agreement with both the International Association of Machinists and Aerospace Workers (IAM) and the United Automobile Workers (UAW).[30] In the past when one major company reached agreement the others generally fell into line. Notwithstanding, the offers emanating from McDonnell Douglas were described by the IAM as 'an insult' and a 90 day strike, by over 20 000 workers, thus, ensued. The strike's impact went beyond all four plants of the company also affecting launch facilities at Kennedy.[31]

With rising costs of materials and labour, many of the shuttle's contractors argued that it was difficult to continue development projects with dollars that bought substantially less than projected in 1972. NASA's FY 1975 funding was based on a 5 per cent inflation factor, but by late 1974 overall levels of inflation on materials stood at around 9 per cent and in some areas approached 10 per cent. The prime contractor, Rockwell, went back to NASA to seek

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30 'Stop Work Meeting at Boeing Aerospace Bargaining Heats Up,' ***The Machinist*** (September 19, 1974), p 1; 'Aerospace Bargaining Focuses on Boeing,' ***The Machinist*** (September 26, 1974), p 1; 'Full COLA Escalator Negotiated at Boeing,' ***The Machinist*** (October 10, 1974), p 2; 'Uncapped COLA, Pensions Win Lockheed Ratification,' ***The Machinist*** (October 31, 1974), p 1.

31 'Nationwide Stike at McDonnell Douglas,' ***The Machinist*** (February 13, 1975), p 2; Nationwide Strike at McDonnell Douglas Halts Aircraft, Missile Production,' ***The Machinist*** (February 20, 1975), p 1; 'IAM Aerospace Strikers, 20 000 solid, Keep McDonnell Douglas Closed,' ***The Machinist*** (February 27, 1975), p 1; 'Strikers Turn Thumbs Down on McDonnell Douglas's Substandard Offer,' ***The Machinist*** (April 3, 1975), p 1; 'St Louis Ratification Ends McDonnell Douglas Strike,' ***The Machinist*** (May 22, 1975), p 1.

more money, but NASA compelled Rockwell to absorb a $5 to $10 million loss under FY 1975 shuttle spending. NASA also informed Rockwell that it could only expect about $700 million per year in shuttle funding during FY's 1976-78: a figure that Rockwell claimed, was about $100 million per year below the amount the shuttle's development schedule required.[32]

In a push for retention of the *constant budget*, NASA continually advised the presidency and the executive branch of the political consequences of sustained funding cuts.

> A great deal of support for the space program in general, and for the shuttle in particular, hinges on program balance. Without this balance we would lose support for the remaining program in the Congress, by the public, and by the scientific and users communities.[33]

> A fiscally imposed slippage of the Shuttle development schedule by the Executive Branch for the third consecutive year may well result in termination of the program. Congress could take it as evidence of an internal Administration intent to create an untenable development environment that would lead inevitably to cancellation. Or Congress could take it as a lack of Administration determination and real commitment to preeminence that would provide an incentive to terminate the program by legislative fiat.[34]

Debates about the necessity of spending taxpayers money on the shuttle, and its place within a host of

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32 K. Johnsen, 'Inflation Boosts Labor Demands,' ***Aviation Week and Space Technology*** (July 23 1974), pp 12-13; Craig Covault, 'Inflation Forcing Shuttle Changes,' ***Aviation Week and Space Technology*** (September 23 1974), pp 20-22; Barry Casebolt, 'Overrun on Costs Of Shuttle Studied,' ***The Huntsville Times*** (April 14, 1974), pp 5-6.

33 Letter from James Fletcher to Roy Ash, Director OMB, July 13, 1973 (NASA History Office Archive, Washington DC).

34 NASA position paper, 18 October, 1974 (NASA History Office Archive, Washington DC), p 2.

national priorities, again reached the Congressional political agenda during 1973 and 1974. Much of the space science community expressed concern that if NASA maintained its commitment to the shuttle within a reduced budget many space science programmes would be cancelled or delayed. The space science field, it was argued, would be 'irretrievably damaged' or 'severely disabled,' if it had to take the shortfall for an underfunded launcher development programme.[35] NASA's upper echelons, although in agreement with the need for increased funding, contested the arguments made against the shuttle. By re-recruiting Mathematica, evidence on the economic returns from the shuttle was again utilized to suggest that, in the long-run, the savings provided by an operational shuttle would result in more money being available for space science, not less.[36] The logic of this argumentation was put forward with such authority that, by the end of 1973 large sections of the space science community were professing that the shuttle would be a valuable asset to scientific research in the 1980s and beyond.[37]

The General Accounting Office, however, were more sceptical. Given the tight budget ceilings, it claimed that

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35 Constance Holden, 'Space Shuttle: Despite Doubters, Project Will Probably Fly' ***Science*** (April 27, 1973) pp 395-397; 'Proxmire "Frustrated" by Capable Defense of Shuttle' ***Space Business Daily*** (April 12, 1973).

36 ***Ibid.***

37 'Space Science Board Finds Shuttle of Great Value to Science' ***Space Business Daily*** (October 11, 1973) pp 203-204.

neither the shuttle nor existing or alternative expendable launch vehicles could be developed and operated.[38] On advising Congress, the General Accounting Office did recommend that:

> if limit budget resources required an austere future space program, then current expendable [launch vehicles] may offer more flexibility for the most economic choice among fewer missions.[39]

By 1975 the General Accounting Office expressed grave doubts about NASA's ability to construct the shuttle on time and within budget. Its main concern was that NASA's budget estimates and schedule goals appeared to be overly optimistic and as a result, the agency's project estimates might be understated and its reserves overstated.[40]

In the Senate, William Proxmire, restated in 1973 that 'he intuitively felt that the shuttle should not be built,' because he believed it was, 'usurping money that is desperately needed for ghetto and other societal problems.'[41] His rationale was questioned, however, by the Californian Senator, Alan Cranston. Cranston argued that, rather than cutting funds from the space shuttle, Proxmire should restore cuts already made by the Office of

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38 GAO, ***Analysis Of Cost Estimates For The Space Shuttle And Two Alternate Programs***, report to the Congress, June 1, 1973 (General Accounting Office Distribution Center, Washington DC), pp 32-34.

39 ***Ibid.*** p 40.

40 GAO, ***Staff Study: Space Transportation System*** February 1975 (General Accounting Office Distribution Center, Washington DC), pp 3, 21, 24.

41 'Proxmire "Frustrated" by Capable Defense of Shuttle,' ***Space Business Daily*** (April 12, 1973) p 236.

Management and Budget. He claimed that the expenditure could be justified because it would create up to 50 000 jobs directly and call on the services of some 10 000 subcontractors and suppliers.[42] Taking an isolationist position, Cranston argued that monies for social programmes should come from the:

> $30 billion the Administration plans to spend to maintain 3 400 US installations and 600 000 service men in 30 foreign countries. ... The shuttle is clearly more important than spending $10 billion on foreign military aid to 64 countries - 27 of whom have military or quasi-military dictatorships.[43]

Pressure was also being felt from both the International Association of Machinists and Aerospace Workers (IAM) and the United Automobile Workers (UAW) as they lobbied the Senate for approval of shuttle funds. In statements to the committee, IAM President, Floyd Smith, and UAW President, Leonard Woodcock, both emphasized that the shuttle could provide up to 70 000 jobs across 48 states; and added that the programme would help ease the aerospace depression, which had taken more than 250 000 jobs since 1969.[44]

The justifications for and the arguments against, spending billions of dollars on a new launch vehicle drew much attention within Congress between 1972 and 1974. But

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42 Alan Cranston, press release from the Office of US Senator Alan Cranston, April 10, 1973 (Smithsonian Air and Space Museum, Washington DC).

43 ***Ibid.***

44 'UAW + IAM = Shuttle,' ***The Machinist*** (April 12, 1973) p 1.

this issue had been well aired during the 1970 and 1971 Congressional debates and yet the opponents of the shuttle had failed to terminate the programme. Another part of the Congressional debates, therefore, centred on the building blocks of NASA's claims to economic and routine access to space: demand and function.

Paragons of Demand.

In the first half of 1970 the Office of Manned Space Flight envisaged an operational shuttle fleet conducting 75 flights per year, at a cost of between $2.7 to $3 million per flight.[45] As NASA's development plans were delayed during 1970 and 1971 and fresh justifications were sought, predictions of future shuttle traffic models fluctuated from a low of 492 to a high of 736, over a 12 year period.[46] After President Nixon's approval of the programme in 1972, NASA's predicted a maximum of 60 flights per year.[47] The politics surrounding NASA's claims of inexpensive access to space and it consequential link to increases in market demand, however, grew in intensity as the shuttle slowly progressed from its conceptual phase into development. Disagreement about the economy of an

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45 NASA, ***Space Shuttle Program Requirements Document Level 1***

46 Heiss K.P, Morgenstern O, ***Economic Analysis of the Space Shuttle System: Volume 1*** (Study for the NASA, Contract No. NASW-2081, January 31 1972); Dale Myers, Memorandum to Deputy Associate Administrator, Planning, June 17, 1971 (NASA History Office Archives, Washington DC).

47 NASA, ***Space Shuttle Requirements Document Level 1: Revision No.4***

operational shuttle tended to converge on NASA's proclamations, made in 1971, that the cost of sending payloads into space would be reduced to $100 per pound.[48] An eminent physicist, senate committee consultant and senior member of the Quadri-Science Incorporation, Ralph Lapp, told the Aeronautical and Space Science Committee in 1972, that the 'true price' of shuttle operations would be $5 100 per pound.[49] Mathematica, the firm contracted by NASA to conduct the an economic evaluation of the shuttle, accepted that launch costs of $100 per pound were not accurate, but it continued to reiterated that the shuttle would eventually produce savings in the region of $4 to $5 billion over a fleet of expendable launch vehicles in the 1980s.[50] NASA, of course, corroborated Mathematica's findings, echoing their claim that:

> Together with NASA's in-house work, [Mathematica's results] conclusively show that the space shuttle is a *clear* [sic] economic choice.[51]

But to some, it was a claim that remained untenable.

In 1973 NASA found that the battle over flight costs was far from over. The Office of Management and Budget's

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48 See for example testimony by Dale Myers, ***NASA Authorization 1972,*** Hearings Before the Committee on Science and Astronautics, United States House of Representatives, p 136.

49 A crucial aspect of the $5 100 figure came from a statement buried within the Mathematica report which reduced the 40 000 pound theoretical payload weight average to 5000 pounds. Ralph Lapp, Testimony to the Committee on Aeronautical and Space Science, ***NASA Authorization For Fiscal Year 1973*** (Washington DC, US Government Printing Office, 1972), p 1071.

50 'Proxmire "Frustrated" by Capable Defense of Shuttle' ***Space Business Daily*** (April 12, 1973), p 237.

51 Emphasis in original. ***NASA Authorization For Fiscal Year 1973*** p 1111.

Evaluations Division, refused to accept NASA's traffic model projections and accused the agency of starting with a 'number that strains credibility' and going up from there;[52] and a 1973 General Accounting Office report to Congress also concluded that the shuttle's operational costs would be far in excess of what was being predicted by NASA.[53] In its report, the General Accounting Office arrived at a very different conclusion from NASA and Mathematica. This disparity arose principally because of a difference in methodologies. NASA had not included development and procurement costs in its calculations and produced an efficiency index which assumed the shuttle would carry maximum capacity on each flight. As many of the planned missions did not require full shuttle capacity and because NASA left out important cost factors such as development and production, the General Accounting Office believed that NASA's comparison between the shuttle and expendable launch vehicles 'was not a meaningful one.'[54] By including both development and procurement costs and computing in an average payload weight over NASA's 1973 traffic model (see table 6:1) the General Accounting Office concluded that costs per pound would be closer to $3 500;

52 Niskanen William, head of the Office of Management and Budget's Evaluations Division, quoted in Claude Barfield, 'Intense Debate, Cost Cutting Precedes White House Decision to Back Shuttle'.

53 GAO, ***Analysis Of Cost Estimates For The Space Shuttle And Two Alternate Programs***, Report to the Congress, June 1, 1973 (General Accounting Office Distribution Center, Washington DC), pp 29-31.

54 ***Ibid.*** p 31.

Table 6:1.

Shuttle Flight Traffic Baseline: 1973.

Year	79	80	81	82	83	84	85	86	87	88	89	90	Total
KSC Flights	12	18	23	22	26	26	40	30	41	40	37	39	354
VAFB Flights	0	18	20	18	24	18	26	19	22	17	26	19	227
Total	12	36	43	40	50	44	66	49	63	57	63	58	581

Source: ***NASA/DOD Space Shuttle Orbiter Fleet Size Analysis***, Prepared by the Office of Manned Space Flight and US Air Force Systems Command, May 15, 1973 (NASA History Office Archive, Washington DC).

more than either existing expendable launch vehicles or a family of new expendable launch vehicles (see table: 6:2).[55]

Ultimately, though, the General Accounting Office concluded that the formulation any cost saving projections were:

> unrealistic, since the systems will be in development until 1979 and any performance savings must accrue over a long period of years.[56]

Nevertheless, the General Accounting Office did clearly state its reservations about the programme.

> NASA's estimates do not remove our reservations that the Space Shuttle will produce cost savings ... while there is uncertainty in cost estimates for both the Shuttle and expendable systems, we believe the degree of uncertainty for the Space Shuttle estimates is greater than for the expendable systems. With these differences in the degree of uncertainty in launch system costs, we do not consider it prudent to place too much confidence in the projected cost savings.[57]

NASA rebutted much of what was being reported by the General Accounting Office. NASA Administrator, James Fletcher thought that it had overestimated shuttle costs and accordingly found no real basis to the report.

> We believe that NASA's economic models have erred, if at all, on the side of conservatism;

55 ***Ibid.*** pp 29-31.

56 ***Ibid.*** p 12.

57 ***Ibid.*** pp 23-24, 41.

Table 6:2.

GAO's Comparison Of Costs Of Placing Payloads In Orbit.

Total launch system cost for aggregate payload weight as scheduled in the 80-mission, 581-flight model:	Current ELV's	New ELV's	Space Shuttle
Aggregate weight (millions of pounds 1979-90)	4.3	4.5	4.6
Total launch system cost through 1990 (billions of 1971 dollars)	$13.3	$11.6	$16.1
Total launch system cost per pound of payload in orbit (1979-90)	*$3 100	*$2 600	*$3 500

* Rounded to nearest $100.

Source: Adapted from Table 3-2 in GAO, ***Analysis Of Cost Estimates For The Space Shuttle And Two Alternate Programs***, Report to the Congress, June 1, 1973 (General Accounting Office Distribution Center, Washington DC), p 30.

> and that this is more true today than when the shuttle was approved in early 1972.[58]

The General Accounting Office however, commented that:

> Although NASA believes its estimates are conservative, our experience with estimates for large systems involving significant uncertainties has taught us to view such estimates with a healthy scepticism.[59]

However, NASA, at this time, had managed to shift the debate away from cost-per-pound as a measurement of efficiency and instead, had introduced 'per mission costs' as the basis upon which to gauge the shuttle's economic advantage.[60]

> [Cost per pound was] an elusive criteria, a siren, it attracted people, but when you analyzed it cost per pound [was not] all that great. It was the cost-per-flight that was important.[61]

Within the Congress, the General Accounting Office report did not gain many allies. A House of Representatives Appropriations Committee, sent instructions to the Library of Congress to prepare an alternative report soon after its release. Entitled, *The June 1, 1973 General Accounting Office Analysis of the Shuttle Program: A Critical Assessment*, it gave quite a scathing appraisal of the General Accounting Office's analysis. Accusing the General

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58 Letter from James Fletcher to Elmer Staats, Comptroller General GAO, May 21, 1973 (NASA History Office, Washington DC).

59 GAO, ***Analysis of Cost Estimates for the Space Shuttle and Two Alternate Programs*** (General Accounting Office Distribution Center, Washington DC), p 35.

60 NASA Comments on the Statement of Dr Ralph Lapp on the Space Shuttle, reprinted in ***NASA Authorization For Fiscal Year 1973*** pp 1108-1112.

61 Charles Donlan, interview with the author, June 7, 1995.

Accounting Office of presenting irrelevant arguments about the cost comparisons between the shuttle and an expendable launch system, the report cited the organization's lack of knowledge about space technology as the foundation of their misconceptions about the programme.[62] An underlying suggestion within the assessment was that those who opposed the shuttle had misconstrued the primary "logic" behind the programme.[63] The General Accounting Office, defended its research conclusions and stressed that its main judgment was the uncertainty involved in any cost projections.[64]

The contested issue of launch costs was closely linked with two other related and equally contestable factors; first, how often the shuttle was going to be launched? And second, how sizable was the demand for a shuttle service going to be? The higher the demand the larger the traffic model. The larger the traffic model the lower the cost. George Rathjens, a professor of political science at the Massachusetts Institute of Technology, advised Congress in 1973 that NASA's traffic models were 'overstated' and that the agency were proposing 'at least twice as many flights as can be justified.'[65] The General Accounting Office, also

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62 'The June 1, 1973 GAO Analysis of the Shuttle Program: A Critical Assessment' reprinted in ***Congressional Record - Senate*** (June 30, 1973) pp S12701-S12702.

63 ***GAO Report on Analysis of Cost of Space Shuttle Program***, Hearings Before the Subcommittee on Manned Space Flight US House of Representatives (Washington DC, Government Printing Office, 1973).

64 ***Ibid.***

65 'Mondale Hoping New GAO Report will Help Kill Shuttle' ***Space Business Daily*** (April 11, 1973), p 230.

very sceptical of NASA's traffic model predictions, described them as 'more uncertain than the costs of the transportation systems themselves'.[66] More worrying for NASA's higher echelons, however, was a growing doubt over the traffic models within the agency itself. Space Shuttle Manager, Robert Thompson recalled:

> There was somethings that came out early ... that may have misled some people. We talked about ... 55 flights a year, something like that. I never felt we would ever get up to anything like that. I mean 55 shuttle flight a year would put more stuff in orbit than you could even think about doing. No one has got that kind of funding or that kind of need, so we never configured any of the logistics or the infrastructure behind the shuttle for much more than about twenty something flights per year.[67]

George English, a chief bureaucrat at Kennedy recollected:

> Nobody here [Kennedy] really believed that we would do 40 or 50 flights per year, that was totally unrealistic. That was guys trying to sell the program, that's exactly what that was. ... [Traffic models of that size were known to be unrealistic at a very early stage in the programme because of] the nature of the environment which you were dealing with. Space is a very hostile environment and it's not like flying an aeroplane. ... The work involved in preparing a vehicle for launch, particularly a reusable vehicle, is pretty horrendous. So there was never any of our knowledgeable people ... who ever thought we would be able to launch 40, 50 shuttle's a year. We use to talk about that and without a serious purpose, a serious goal, there was no need for it. People were talking about communication satellites, but how many do you think we would put up?[68]

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66 GAO, ***Analysis Of Cost Estimates For The Space Shuttle And Two Alternate Programs*** (General Accounting Office Distribution Center, Washington DC), p 12.

67 Robert Thompson, interview with the author, September 9, 1995.

68 George English, interview with the author, July 26, 1995.

Hans Mark, then Director at NASA's Ames Center, reflected:

> The whole cost-effectiveness argument, I believe, was fraudulent from the start ... and I said so in the private councils at the time, but I didn't want to get thrown out so I never went public with it.[69]

> I remember that we had a lively discussion with Heiss during his visit because the flight rate that both he and NASA headquarters were projecting ... were substantially higher than the launch rates in the early 1970s. Many of us were unhappy with the conclusions because we could not honestly reconcile ourselves to the shuttle launch rates being forecast.[70]

NASA's own launch rate had peaked at 31 in 1966; by 1973, it was down to 13.[71]

Another focus for the misgivings surrounding NASA's traffic models centred around the relationship between NASA and the contractors who provided the data. A Vermont based "citizens group", the Universe Astronautics Foundation Inc., opened this question in an attempt to inject some distrust over the validity of Mathematica's results. Central to their argument was the claim that both Lockheed and Aerospace had vested interests in the shuttle and, therefore, could not be seen as independent from NASA.[72] The involvement of Lockheed and Aerospace in the shuttle's cost-effective analysis and the effect of that involvement

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69 Hans Mark, interview with the author, September 8, 1995.

70 Hans Mark, ***Space Station*** p 49.

71 Including DOD launches peak year activity stood at 73 in 1966 and the slowly dropped to 23 by 1973. NASA, ***Pocket Statistics*** (Washington DC, NASA History Office, 1995), p B4.

72 'Space Shuttle Antagonists' ***Space Business Daily*** (June 5, 1973), p 197.

on Mathematica's results was a concern that also found echoes within NASA's own rank and file. Adelbert Tischler, Director of the Chemical Division of the Office of Advanced Research and Technology wrote:

> On presenting its conclusions to Congress Oskar Morgenstern ... opened his statement with a declaration that the Mathematica results could be no more accurate than the contractor's data from which they were drawn. To me (and I was there) that was an open hint that Oskar saw shortcomings in those data.[73]

Nevertheless, by the end of 1973 the confidence of the cost-effectiveness arguments was 'frustrating' opponents in the Congress.[74] Once the Mathematica study had filtered through, many of the shuttle's adversaries began to swing over to the NASA camp.[75] The cost-effectiveness arguments had penetrated to such a level that many in Congress were willing to accept them.

> Senator Proxmire ... was a vocal opponent of the shuttle and then one talk I gave after he had seen this [Mathematica study] he said he gave up fighting the economics, there was too much in there for him to combat, he accepted it finally.[76]

The uncertainty of what a future space programme would look like, tended to favour the NASA position. The debate on economic questions had become extraneous because the issues

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73 Adelbert Tischler, letter to the author, November 13, 1996.

74 'Proxmire "Frustrated" by Capable Defense of Shuttle' ***Space Business Daily*** (April 12, 1973), pp 236-238.

75 Bill Sneed, interview with the author, August 21, 1995.

76 Charles Donlan, interview with the author, June 7, 1995.

were based on predictions that stretched as far as 30 to 40 years into the future so neither side could really prove its case.[77] NASA and its supporters had thus, successfully shifted the debate temporarily away from economics. Unpredictability meant flexibility. The shuttle, touted as a flexible technology promised an adaptable new space transportation system that could meet the needs of an uncertain future in space. George Low's premise, that the importance of the shuttle lay in its new capabilities, had permeated enough for one Senator to comment that he saw:

> merit in the argument that the Space Shuttle represents *the next logical step* in space.[78]

Function, however, was another issue in dispute.

The Politics of Function.

In 1972, Ralph Lapp also questioned NASA's most celebrated attributes of the shuttle; the promise of versatile space operations through the retrieval, refurbishment and repair of satellites.

> The increasing complexity of orbital devices calls for a much greater payload of checkout devices ... It is not a matter of a man with a screwdriver fixing mechanical things. I know in some cases, even the men who are putting up these scientific satellites prefer their own laboratory only to check them out. Professor Van Allen told me that quite recently. ... Furthermore, if you look at the Comsat satellites, they prefer to use

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77 ***The National Space Programme,*** Congressional Record, the Senate (May 30, 1973), pp S9863-S9864; Ranking GOP Commmittee Member Opposes Proxmire on Shuttle' ***Space Business Daily*** (June 4, 1973) p 188.

78 Charles MacMathias. ***Ibid.*** p S9863, my emphasis.

> lighter satellites and more of them. ... I am sure Comsat Corp would be very reluctant to send a Space Shuttle up, bring the satellite down, repair it, and send it up again. I believe they would be more prone to replace it with a more efficient satellite.[79]

The DOD's top brass however, had formed a convincing rationale based upon the shuttle's new capabilities to support the programme. Its reaffirmation of support in 1972 served to assure patronage for the shuttle within Congress during that critical year. Secretary of the Air Force, Robert Seamans, concluded his testimony to the Senate Committee on Aeronautical and Space Sciences by saying;

> I believe *the next logical step* is to move toward development of the Space Shuttle. If we proceed step by step, we should be able to develop a Shuttle that will offer significant advantages in the way we operate and perform our missions in space. Also, if we are successful in our developmental efforts, we could open new avenues for a greater range of applications of space which would benefit all of mankind.[80]

John Foster, Director of Defense Research and Engineering at the DOD, told the Senate Committee that:

> The Department of Defense can benefit from the new operating capabilities of the Shuttle for future military space operations, [because of its ability to] recover, adjust, modify, repair, and return selected payloads and thus make more effective use of our space hardware.[81]

What Ralph Lapp had deemed an unimportant function for both scientific and commercial users, the US military saw as

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79 Ralph Lapp, Testimony to the Committee on Aeronautical and Space Science, ***NASA Authorization For Fiscal Year 1973*** (Washington DC, US Government Printing Office, 1972), pp 1077-1078.

80 Robert Seamans, ***Ibid.*** pp 1041-1042, my emphasis.

81 John Foster, ***Ibid.*** p 1000

potentially a valuable asset. The technology's promise of routine access to space combined with short turnaround times were viewed by the DOD as superior advantages worth pursuing. An ability to resupply or deploy new or refurbished payloads quickly in times of crisis held a great appeal for the DOD.[82] Underlying the military agenda however, was the opportunity for it to become actively involved in human space flight; something the DOD had coveted since the beginning of the space programme.

> As manned operations become more routine and as scientists and technicians are equally able to accompany their payloads in space, our use of man in military space operations will become practical.[83]

Paradoxically it was a NASA failure in 1973 that served as a further justification for an investment in the shuttle. A rehearsal for continuous operations in orbit was provided by Skylab, the centre piece of NASA's Apollo Applications Program. Constructed for both scientific and industrial applications, Skylab was a two storey orbiting laboratory converted from the upper stage of the giant Saturn V Moon rocket. It was an ill-fated programme however, plagued with problems from the very start. Unforseen aerodynamic loads broke off part of the station's external heat and meteoroid shield and caused the loss of one of the two solar array systems on its maiden flight on

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82 *Ibid.*

83 *Ibid.* p 1000

May 14, 1973. The second solar array also did not open, leaving Skylab with no power and without protection from the searing heat of the sun.[84] A rescue crew was sent up to repair Skylab on May 25 and after 28 days of work, involving a number of spacewalks, Skylab was deemed fully operational.[85] Two further visits were made to Skylab each involving space walks and medical, scientific and industrial experiments. The final mission came on November 16, 1973. During this mission NASA unwittingly learnt some crucial lessons on the psychological problems associated with long term stays in space. Relations between Houston and Skylab 4's crew, Gerry Carr, Bill Pogue and Edward Gibson, soon broke down after it was discovered that the crew were attempting to hide Pogue's affliction with space sickness. The result was an escalation of conflict between mission control and the crew. Among a catalogue of complaints, the crew found that: the levels of noise inside the station impaired their sleep, the internal tannoys were unreliable, the drinking water was filled with bubbles, which led to chronic flatulence, and they had become bored with their diet and their replacement clothes, which were all the same colour. Combined with continual changes to, and increases in, their workload the crew eventually went

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84 NASA Investigation Board, 'The Initial Flight Anomalies of Skylab 1' Francis Hoban, William Lawbaugh, (ed) ***Readings in Systems Engineering*** (Washington DC, NASA, Scientific and Technical Information Program, 1993), pp 181-199.

85 The crew members were Charles Conrad, Paul Weitz and Joe Kerwin. Frank Anderson, ***Orders of Magnitude*** pp 82-84; Linda Neuman Ezell, ***NASA Historical Data Book Volume III*** pp 93-108; Nicholas Booth, ***The Encyclopedia of Space*** (London, Brian Trodd Publishing House Limited, 1990), p 113-115.

on strike. Hasty compromises by mission control soon eased the situation and after a short period they resumed work. The crew eventually returned to Earth after spending a record 84 days in space.[86]

Skylab was short lived, but it provided a welter of medical and scientific data on long stays in space. The programme also served NASA well as a public relations vehicle, accentuating the potentials of human operations in near Earth orbit. It demonstrated that humans could withstand long stays in space and still perform "useful" work. Emphasis had also been placed on industrial applications in a zero-gravity environment; a necessary slice of propaganda to justify NASA's shuttle programme and endorse the vision of a commercialized and industrialized space environment of the future.

The space walk repairs carried out on Skylab had coincided with the Congressional debates, providing a demonstration of the shuttle's future possibilities. Political rhetoric had adroitly turned misfortune into powerful vindication. After Skylab, one Senator commented:

> Moreover, substantial savings may arise from eliminating such costly losses as the $100 million orbiting astronomical observatory and the $70 million Mariner Mars failure. These costly failures would very likely have been avoided had a Space Shuttle been available. In this connection, the repair of Skylab is a very good demonstration of repair work that a Shuttle crew

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86 *Ibid.*

> can carry out on a future malfunctioning satellite.[87]

Another Senator expressed much the same view:

> In the era of Space Shuttle, ... hardware which was damaged or failed would no longer have to be abandoned. The successful and timely repair of a Skylab would thus become normal operations of space flight by this Nation. This appears to me to be a very logical way to do business, and an example of just one of the many valuable roles which the Space Shuttle can play.[88]

"Normal operations" in space would, nonetheless, involve a lot more than the activities of astronauts in orbit.

Despite criticisms, in 1975 NASA's financial problem, its consequences, and the continued justifications for developing the shuttle within a restricted budget, had minimal political impact, coming as they did in the aftermath of the Watergate scandal. Between 1973 and 1974 the Nixon Adminstration fell from one political crisis into another. Vice President Spiro Agnew was forced to resign in October 1973 on State corruption charges; and accusations of a cover up, which involved pay-offs, pressuring the FBI and the erasure of key conversation tapes, resulted in many of Nixon's aides being ordered to resign in the same year. Nixon himself managed to hold on to power through 1973 and

87 Cutting from the Congressional Record, the Senate, June 30, 1973 (NASA History Office Archive, Washington DC).

88 Charles MacMathias, ***The National Space Program,*** p S9864.

into 1974, but with impeachment by the Congress pending, he was finally forced to become the first president to resign from office on the 8 August 1974. The affair marked the end of the imperial presidency and a resurgence in the power of Congress. President Gerald Ford attempted to restore confidence in the office of the presidency and provide a 'period of healing,' but he was to experience unprecedented opposition from the Congress and a growing cynicism from the American public with public institutions.[89] James Fletcher's appeal to the new president to restore NASA's funding and support both the space shuttle and the US space programme, contained within it a reflection of the crisis that besieged US government at the time:

> As a matter of conscience and duty, I must inform you of the steady erosion of the United States space capabilities and of the dangers this poses. ... If the civil program continues to be held below its critical threshold, we run a real risk of foregoing rich benefits in international prestige, military spinoffs, economic and industrial stimulation, and constructive noninflationary employment. ... In my view we have reached a breaking point. ... Even the usually conservative financial community is recognizing that signs of a national technological crisis - and the shrinkage of the NASA program has been a major contributor to that crisis.[90]

89 David McKay, ***American Politics and Society*** (New York, Basil Blackwell, 1987); M.J.C. Vile, ***Politics in the USA*** (London, Hutchinson, 1976); Jonathan Schell, ***The Time of Illusions*** (New York, Vantage, 1975).

90 Letter from James Fletcher to President Ford, June 4, 1976 (NASA History Office Archive, Washington DC).

***Enterprise* Rolls-out.**

Despite the financial and political problems which NASA faced, Enterprise the first test article orbiter was produced on time. For NASA it was an important milestone in the shuttle's development. For many members of the American public it was an opportunity to escape political cynicism and marvel at the technological sublime.

Following aerospace tradition, the shuttle was unveiled to the public at a roll-out extravaganza at the Palmdale assembly plant in California on September 17, 1976. Over 2000 guests, three major television networks, two senators, two congressmen and six cast members from the television series *Star Trek* attended the ceremony. As Enterprise emerged from its hanger the Golden West Air Force band rolled drums and played the *Star Trek* theme tune. The reason *Star Trek* played such a prominent role was the result of a concerted write-in campaign to the White House by fans demanding that NASA change the name of the first orbiter from its original Constitution to the name of the fictitious star ship Enterprise. During a 45 minute meeting on September 8, 1976, President Gerald Ford notified NASA Administrator, James Fletcher of the campaign and made it known that Enterprise was also his preferred choice. It is not clear why Ford intervened in such a trivial part of the shuttle programme, since for most of his presidency he left the project to its own devices. Coming at the end of an election year, Ford may have considered that this populist manoeuvre would win him some critical votes; at least from the *Star Trek* fan club. Fletcher's agreement with Ford over the naming of the first orbiter did cause some concern among a number of NASA officials, because of the commercial and marketing activities associated with the series. Other agency officials however, saw the name as giving the shuttle ready recognition. The mythology of an American-led multinational corps of missionaries spreading peace by enterprise suited the post-lunar propaganda and served to justify the continuing exploitation of space.[91]

An estimated 35 000 to 40 000 people jammed into Rockwell's Palmdale plant to catch a glimpse of Enterprise on September 18, 1976 during an open house day. Open house had originally been designed for Rockwell employees, but media publicity indicated that it would be open to the public, which resulted in a much larger turnout than expected.[92] Ordinary members of the public also lined the roads to catch a glimpse of Enterprise when it was moved by trailer the 35 miles from Palmdale to the Hugh L. Dryden Flight Research Center on 31 January 1977 (see Print 6:1).

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91 Thomas O'Toole, 'Space Shuttle Orbiter Shown for First Time in California,' ***Washington Post*** (September 18, 1976); 'Shuttle Orbiter Named,' ***Aviation Week and Space Technology*** (September 13, 1976), p 26; Dale Carter, ***The Final Frontier*** pp 200-201.

92 'Visitors Jam Shuttle Site,' ***Daily Ledger-Gazette*** (September 20, 1976).

Print 6:1

Courtesy of NASA.

Chapter 7

Fabrication, Test and Modification

> Science and technology lie at the heart of social asymmetry. Thus technology both creates systems which close off other options and generates novel, unpredictable and indeed previously unthinkable options. The game of technology is never finished, and its ramifications are endless.[1]

Conditions of Development Practice.

Budget cuts, costs overruns and inflation were all significant shapers of technological development practice at NASA, as Johnson's Director, Christopher Kraft recollected:

> At the time of developing [the space shuttle] we also had to change the character of NASA, at least the manned space flight parts of NASA.[2]

Up until the shuttle, cost, although not a non-factor, was not *the* factor which determined NASA's practices. During Apollo, development practice was primarily shaped by its schedule. The criteria for success involved not just a working technology, but completion of the mission within an established deadline. Cost was thus a variable that could be tailored to the needs of the technology and the

1 Michel Callon, 'Techno-Economic Networks and Irreversibility,' John Law, (ed) ***A Sociology of Monsters: Essays on Power, Technology and Domination*** (London, New York, Routledge, 1991), p 132.

2 Christopher Kraft, interview with the author, September 1, 1995.

schedule.[3] As Johnson engineer, Norman Chaffee recollected, many of the Apollo/Saturn Moon rocket's requirements had at least two, if not three, alternate technological solutions running in parallel:[4]

> In the good old days of Apollo, if you had an idea, [or] you recognized an area of risk in the program, it was very easy to go and get money to work on a technology or an alternate concept that would provide you [with] a viable backstop; in case you did run into a problem.[5]

Nevertheless, the shuttle had to be built within a fixed price contract. For NASA, this was 'unheard of:'[6]

> Cost became one of *the* major factors and we had to turn the whole organization, the whole management scheme, ... in fact the aerospace industry had to be modified, to design [and build] something of that complexity and that amount of new technology.[7]

NASA had to convince its engineers, scientists and administrators that cost was as a big a factor as the aerodynamics or the schedule. Cost thus drove both the schedule and the technological potentialities.

> By in large everything we did, from the choice of what the concept was, to the breadth of the test program, to the number of what if situations, ... there was almost no backup program. We were committed to our first approach and only in very rare cases would the program manager provide any money because I am so concerned about the risk of

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3 Christopher Kraft, interview with the author, September 1, 1995; LeRoy Day, interview with the author, June 26, 1995; Norman Chaffee, interview with the author, September 6, 1995.

4 Norman Chaffee, interview with the author, September 6, 1995.

5 Norman Chaffee, interview with the author, September 6, 1995.

6 Christopher Kraft, interview with the author, September 1, 1995.

7 Christopher Kraft, interview with the author, September 1, 1995, my emphasis.

> this particular element that I want to fund a backup activity.[8]

> In the shuttle money was part of the design criteria. When you design a flying machine you always have a weight bogey that you have to design too. Well, in the shuttle, not only did we have a weight bogey, but we had a dollar bogey that everything had to be designed to also.[9]

Budget constraints had impacted on the shuttle's development schedule each year since its inception. A nine-month slip was required in 1972 to accommodate an $85 million reduction in the FY 1974 budget and another 6-months' slip was incurred in 1973 to meet an $89 million reduction in the FY 1975 budget.[10]

> As the press of the budget, the limitations of the budget, became more and more apparent ... we began to push things off; we began to lose schedule. We used schedule as the rubber band and the schedule began to slip.[11]

Schedule slippage, though, was not the only victim of restricted funding. In 1974 NASA formed a Space Shuttle Programme Costs and Requirements Committee to initiate some shuttle programme changes to reduce costs. The cost and requirements committee was made up of persons outside of the shuttle programme to give NASA a fresh look at the development effort, but it was not permitted to alter basic shuttle requirements. NASA's upper management eventually

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8 Norman Chaffee, interview with the author, September 6, 1995.

9 Samuel Beddingfield, interview with the author, July 31, 1995.

10 NASA, position paper, 18 October, 1974 (NASA History Office Archive, Washington DC).

11 Christopher Kraft, interview with the author, September 1, 1995.

approved 26 changes in the shuttle programme to save an estimated $360 million over a three year period, which included: deferral of ground support equipment, deletion of a number of test programmes and deferral of some hardware construction.[12]

> What we were doing was basically saying that we will take a schedule slip, or we will take a performance decrement, but we are committed to this thing we chose and if we have to leave off some tests and analytically estimate the performance in certain realms and do a smaller number of test, we [will] do that.[13]
>
> As a design requirement for the shuttle, we did not ... build any development hardware. We just went right straight to the final configuration and built the hardware and said that is what we will test; that's what we will fly if it tests ok, rather than going through a whole development phase where you built various types of hardware ... and then selected from that experience what you were going to fly with.[14]

NASA's development strategy for the shuttle was thus described as "success-orientated". It was a strategy that gambled on each piece of development hardware and its subsequent verification test succeeding on the first attempt. Simply stated, it was the inverse of Murphy's law; an assumption that everything would go right first time.[15]

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12 R.H. Gray, memorandum for distribution, October 4, 1974 (Kennedy Space Center Archive, Florida); Reports on shuttle cost deletions and deferral actions for FY 75/76, September 1974 (NASA History Office Archive, Washington DC); 'NASA Decides on 26 Changes in Shuttle Program to Save $360 Million' ***Defense/Space Business Daily*** (December 27, 1974), p 288.

13 Norman Chaffee, interview with the author, September 6, 1995.

14 Christopher Kraft, interview with the author, September 1, 1995.

15 David Dickson, 'Test Failures May Hold Up Space Shuttle Schedule,' ***Nature*** (April 6, 1978), p 482; 'Shuttle Problems Compromise Space Program,' ***Science*** (November 23, 1979), pp 910-914.

History had equipped NASA with the confidence to employ a "success-orientated" approach to the development of the shuttle.[16] A significant difference between the shuttle and NASA's previous space programmes was the breadth and depth of the knowledge and experience base of the US space flight community.

> We were a little bit more comfortable with ... the physics of flying in space. ... By the time we had got to the shuttle program we had flown Apollo, ... we had done a lot of things that we were going to do again.[17]

> Shuttle benefitted from the standpoint that many of the people who had worked on shuttle had cut their teeth on the Saturn program, both at Johnson and Kennedy and also here [Marshall]. People we had in management slots had a lot of experience, a lot of knowledge, they had been through problems before.[18]

At the outset of the shuttle's design there existed a concrete foundation from which the technology could be built. Scientists, engineers and administrators faced fewer unknowns than they did at the commencement of human space flight. A welter of different methodologies, practices, knowledge and technologies devoted to solving the problems of human space flight had already been generated. Numerous solutions could thus be applied again and unique requirements could be addressed by drawing on previous experience. Space technology was considered by many to be

16 Christopher Kraft, interview with the author, September 1, 1995.

17 Herb Yarbrough. interview with the author, September 5, 1995.

18 Robert Lindstrom, interview with the author, August 17, 1995.

relatively mature. The shuttle was represented as a "next step" technology; a programme that would bring known techniques together in a new form.

The old, thus, shaped the new. NASA thought that the innovation process would be a lot less complicated for the shuttle:

> The innovation process was kind of something that was just hoisted upon us. We said ok, were going to use the same technology that got us to the Moon and back. We learnt an awful lot in developing Apollo ... we are not going to make the same set of mistakes again.[19]

Problem solving, itself, would be a lot different:

> As often as we could we just avoided problems rather than solve them. ... If you could just avoid it, ignore it, or override it, you just did that, you didn't try to get too sophisticated.[20]

But, many of the requirements for the shuttle were very different from Mercury, Gemini, or Apollo.[21] That was a different era and the technology was designed and fabricated under notably different conditions. With the shuttle, the management of cost and political uncertainty had become important considerations. Each would have to be monitored and manoeuvred through very carefully. Nevertheless, NASA was primarily a technical organization

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19 Norman Chaffee, interview with the author, September 6, 1995.

20 Robert Thompson, interview with the author,

21 Norman Chaffee, interview with the author, September 6, 1995.

and 'making the shuttle fly, very clearly, was still the most pressing need'.[22]

History was also entrusted with the authority to introduce another radical shift in NASA's development and testing practice: flight of the shuttle's first orbital test with a crew on board. The beginnings of human space flight was a perilous adventure. Space is a hostile environment and the expanse of the unknowns at the debut of human exploration were infinite. As the risks were many and the stakes were high, trust was centred on the machine. Astronauts were supplementary to the technology rather than an integral part of it. Like the monkeys that preceded them, the first explorers into space had little to do but sit there and enjoy the ride.[23] Consequently, during Mercury, Gemini and Apollo, the first orbital test flights were automated. Humans were not "plugged into" the system until there was enough confidence in the technology. The space shuttle, however, symbolized a new era in space travel; one in which humans played a much larger role. Nevertheless, cultural expectations resulted in a propensity towards automation. Many of the systems designers were working on the basis that first orbital flight would not be piloted, but stirrings within NASA were considering a different avenue altogether.

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22 Bill Sneed, interview with the author, August 21, 1995.

23 Tom Wolf, ***The Right Stuff*** (London, Jonathan Cape, 1979).

In August 1973, engineers at Johnson requested assistance from the Langley Research Center to investigate its proposal that a crew should be on board the shuttle's first orbital test flight. After a short period, Langley concurred with Johnson, arguing that a crew on the first orbital test flight would increase the success of the mission, because they would be able to intervene in certain emergency situations. In addition, Langley thought that the presence of humans would also add an incentive for increased reliability at all levels of development.[24] Johnson thus pushed its idea forward, but it was up against a strong tide of tradition, as Johnson's Director, Christopher Kraft recalled:

> Well, we had a large argument about that, as you would expect. It took a lot of convincing of our management and of ourselves that we didn't have to fly the machine unmanned first, that we could take advantage of the redundancy of the human being in the system to correct any of the unknowns ... that we'd come up against. ... there were a lot of people who thought we were crazy ... thought that the vehicle would burn up [on reentry]. Some didn't think we could control it; some didn't think that man could fly it properly during reentry, that he'd have vertigo. A lot of people thought the configuration we had was going to blow up on the pad.[25]

By the end of 1973, though, other sections of NASA's upper management were also affirming the benefits of having

24 W.H. Phillips, Chief of Flight Dynamics and Control Division, Langley Research Center, memorandum for distribution, December 6, 1973 (NASA History Office Archive, Washington DC).

25 Chris Kraft, interview with the author, September 1, 1995.

humans on the first orbital test flight. Kennedy Director, Kurt Debus told NASA Associate Administrator, Dale Myers:

> I believe that there are programmatic advantages in going "manned" for the first launch. Certainly there is a cost saving to be realized by avoiding an additional unmanned configuration. These costs are incurred through additional automation, additional redundancy not required with a man in the loop, and additional processing time required by configuration changes. ... I believe our knowledge and experience have progressed to the point that we can adequately assure crew safety. ... I believe that a "man in the loop" greatly enhances a first mission success. ... loss of an orbiter on the first mission would be critical to the Shuttle program. Due to this, I believe the Shuttle program is somewhat different from past programs in that we should exceed past precedents and efforts ... to assure success of the first mission. ... Basically, such a flight is to test the unknown. If analysis and test programs indicate these unknowns are of a lethal nature, then such a flight should not be made. If on the contrary, the unknowns are of a nature that can be overcome by man, then the mission should be manned.[26]

By mid-1974 the debate surrounding crewed versus non-crewed first orbital flight had reached the highest echelons of NASA. The agency's initial approach, to design for a crew on the first orbital flight, but retain the automated option, was proving 'undesirable' because design decisions at the detailed level were slow; and it was felt that the emerging design was being heading towards greater automation. A crewed first orbital flight, it was argued,

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26 Letter from Kurt Debus to Dale Myers, November 1, 1973 (Kennedy Space Center Archive, Florida).

provided the greatest probability of success at lowest cost and at the earliest schedule.[27]

> We took a look at flying it unmanned and it was an economic trade-off versus a schedule trade-off versus risk. We figured out how we could fly it unmanned, but we felt confident enough in the vehicle that we did not need to spend that kind of money ... and we knew that if we flew it manned one time that we would be alright, but it was a risk.[28]

NASA's new Associate Administrator for Manned Space Flight, John Yardley, confirmed his support for a crewed first flight in mid-1974.

> I have recently reviewed all the facts pertinent to a decision regarding manning the first Shuttle orbital flight. Based upon this review, I have determined that we should proceed with design, development, and testing of the shuttle considering only a manned first flight ... This is based on my judgement that the manned benefits of greater probability of success ... far outweigh the crew and program risks involved.[29]

Shortly after, the decision to have a crew on the first flight was endorsed by Associate Administrator, Rocco Petrone, Deputy Administrator, George Low and Administrator, James Fletcher on July 19, 1974.[30] Although, not everyone at NASA agreed with this decision, as

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27 Notes from meeting at NASA Headquarters on the manning of the first orbital flight, July 9, 1974 (NASA History Office Archive, Washington DC).

28 Samuel Beddingfield, interview with the author,

29 Memorandum from John Yardley, Associate Administrator for Manned Space Flight, to Rocco Petrone, Associate Administrator, July 18, 1974 (NASA History Office Archive, Washington DC).

30 The recommended course of action was to proceed with the design and development of crewed version of the shuttle with a review of the risks 18 months before scheduled first flight. If this review considered the risks too great then a retro-kit could be implemented to automate the first orbital flight. ***Ibid.***

Marshall's Director of the Science and Engineering Directorate, James Kingsbury recalled:

> It would not have taken an awful lot to have flown unmanned, but the determination was made early on that it would have cost a lot of money to develop the software to permit that. In fact, I seriously doubt that that is the case, because on the way up the crew is a passenger, on the way back the crew can be a passenger until they get on the runway and then they have to step on the brake and steer. But it was seen as a big money saver and, therefore, enthusiastically supported by the politicians, [but] those of us who were very conservative engineers didn't like it. ... It ... said that the probabilities of something happening to the crew were greater than they normally had been in the past, because this would be a system that had not been tested in flight. And you cannot do all of the testing to represent the complete flight system on the ground. So there [were] many many unknowns.[31]

Indeed, far from being a conglomeration of established technologies, simply utilized in a new form, the shuttle represented a major innovation in many areas.[32] One of those areas was the shuttle's main rocket engines. Getting the engine to work and work consistently over 100 flights represented one of the toughest challenges, because it housed a myriad unknown quantities.

Fabrication and Test of the Main Engines.

In mid-1975 the first test of a shuttle engine was conducted at NASA's National Space Technology Laboratory in Mississippi. The test itself lasted less than a second, but

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31 James Kingsbury, interview with the author, August 16, 1995.

32 Christopher Kraft, interview with the author, September 1, 1995.

it marked a critical turning point in the engine development programme.[33] Component testing, conducted at Rocketdyne's Santa Susana Field Laboratory in California, had not proceeded smoothly. The traditional practice of testing each component individually on a component test stand had been hindered by the very integrated nature of the staged combustion engine design (see figure 7:1). Simulating the rest of the engine to test a single part had turned into a major development programme in itself. Rocketdyne found that it was constructing component test stands that were essentially complete engines. To NASA's upper management this appeared an expensive and time consuming method. Consequently, at the end of 1974 shuttle programme management terminated the component test programme and changed the approach to building a complete test engine:[34]

> We changed the program around and moved as quickly as we could to build an engine so we could get it down to [the National Space Technology Laboratories at] Mississippi and do the testing.[35]

Programme activity thus shifted to building what was called an integrated subsystem test bed engine. This was essentially an engine, but it was not built to flight

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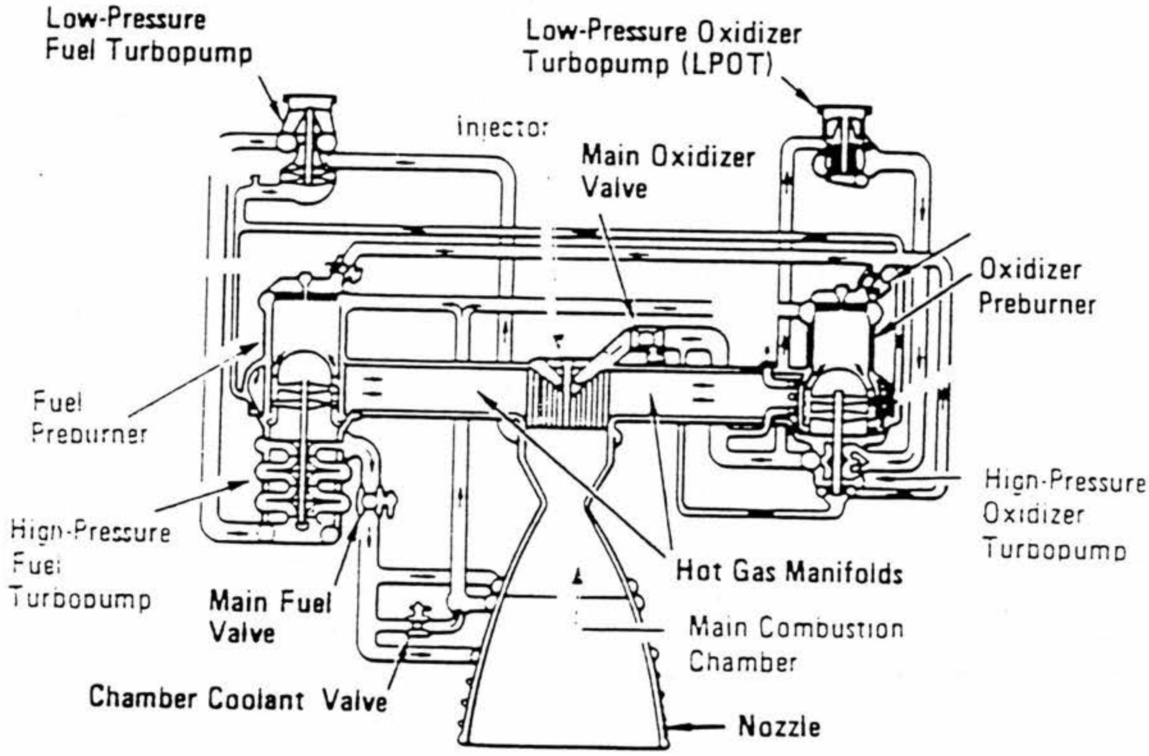
33 The Mississippi test site had originally been constructed for static tests on *Saturn V* engines. During 1973 the facilities were modified to accommodate the shuttle's main engines. Craig Covault, 'Shuttle Engine Passes Critical Milestone,' ***Aviation week and Space Technology*** (June 30, 1975), pp 37-42; Dennis Jenkins, ***Space Shuttle*** pp 153-154.

34 James Kingsbury, interview with the author, August 16, 1995; Robert Lindstrom, interview with the author, August 17, 1995.

35 Robert Lindstrom, interview with the author, August 17, 1995.

Figure 7:1.



Source: John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Chaffee Norman. Ed. ***Space Shuttle Technical Conference: Part 1.*** (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985).

hardware specifications. It was larger and heavier than a flight engine and did not include a computer controller or a full size nozzle. The main functions of this engine was to "prove" that the concept would work and to test components such as the turbopumps.[36] In the original specifications, sub-system hardware was expected to perform 100 flights before major refurbishment. For the main engines, this specification was translated into a duration target to confirm the reliability of the design.

> We had set ourselves a target, since it hadn't been done before we had to make it up, that we had to have 60 000 seconds on an engine before we fly people on it.[37]

The 60 000 seconds requirement was largely based on historical data. The Apollo J-2 engine design had run for 60 000 seconds during testing before it was certified. The same requirement, therefore, followed through into the shuttle engines. Of course, the requirement did not refer to a single engine, but to the engine design. The 60 000 seconds represented a mark of confidence in the design; the cumulative test time of a number of engines and engine components.[38] An important aspect of the engine's design was the use of line replaceable units. Each engine component was designed to be interchangeable, thus allowing

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36 Craig Covault, 'Shuttle Engine Passes Critical Milestone,' ***Aviation Week and Space Technology*** (June 30, 1975), pp 37-42.

37 James Kingsbury, interview with the author, August 16, 1995.

38 James Kingsbury, interview with the author, August 16, 1995.

engine maintainability over the 100 flights. Notwithstanding, each line replaceable unit had to adhere to a cost-effective criterion so a reusable target of 27 000 seconds was established for each replaceable component.[39]

Marshall and Rocketdyne's initially approached engine fabrication and testing using classical techniques: internal engine environments were predicted; loads and stresses were calculated; models were developed; and design tolerances were created. Many of the original design values were drawn from NASA's previous engine programmes, but it soon became apparent that the classical approach was not, in general, accurate enough to predict internal environments; and the engine could not be accessed in all areas to measure these environments.[40] The goal of high performance and high efficiency at very low weight pushed both technology and technique to their limits. The engine design had looked good on paper, but getting the system to work took much longer than expected, because the engine did not operate the way it was initially intended.[41] By the end of 1975, the engine test programme had fallen behind schedule, because of various hardware and software

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39 Robert Ryan, Larry Salter, George Young, Paul Munafo, 'SSME Lifetime Prediction and Verification, Interacting Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402; John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 600-617.

40 ***Ibid.***

41 Max Faget, interview with the author, September 9, 1995; Robert Lindstrom, interview with the author, August 17, 1995.

problems.[42] Marshall and Rocketdyne, therefore, had to incorporate a different approach to their fabrication and testing techniques, which utilized data from hardware failures to build up empirical knowledge of how the engine worked.[43]

One of the first hardware failures occurred during a test on September 11, 1975, when a fuel pre-burner oxidizer valve leak resulted in an oxygen rich mixture that damaged the turbine in the high-pressure fuel pump. Marshall and Rocketdyne initially traced the problem to an unbalanced pressure load on the valve, which led to a failure of its static seal. As the engine tests progressed, however, the fuel pre-burner oxidizer valve continued to let propellant flow into the pre-burner combustors after the valve was closed. Further analysis showed that the failures were the result of a design fault. A number of traps existed within the valve that permitted fuel to collect and enter the combustors after the valve had closed. The valve thus had to be redesigned so that traps downstream of the shut-off mechanism no longer existed.[44]

An altogether more elusive problem, which eventually became known as sub-synchronous whirl, troubled Marshall as

42 Craig Covault, 'Shuttle Engine Delays Overcome,' ***Aviation Week and Space Technology*** (July 5, 1976), pp 43-49.

43 Robert Ryan, Larry Salter, George Young, Paul Manafo, 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402.

44 Craig Covault, 'Space Shuttle Engine Testing Delayed,' ***Aviation Week and Space Technology*** (October 6, 1975), pp 20-21; Craig Covault, 'Shuttle Engine Delays Overcome,' ***Aviation Week and Space Technology*** (July 5, 1976), pp 43-49.

the engine programme moved into 1976. Many of the tests during 1975 had been of short duration at low power levels. The test programme was intentionally phased in terms of power and time, so that Marshall and Rocketdyne could gain more knowledge as they worked towards a full duration test at full power. As the longer duration tests at higher power levels progressed, it was discovered that higher vibration levels than desirable occurred in the high-pressure fuel turbopump. Within the turbopumps is a large shaft that spins at speeds of over 40 000 revolutions per minute at full power. As the shaft built up speed another oscillation within that oscillation occurred, causing rotor instability, which eventually destroyed the pump and damaged major sections of the engine.[45] The problem perplexed both Rocketdyne's and Marshall's engineers for many months, as Rocketdyne engineer, Lee Solid recalled:

> Nobody anywhere in any industry had any knowledge or any experience in this new phenomena called sub-synchronous whirl. ... I'm still not sure that we totally understand it.[46]

The sub-synchronous whirl problem forced Marshall to continue engine tests at 75 per cent power level, delaying the first test at full power until a solution could be

45 Lee Solid, interview with the author, July 26, 1995; Adelbert Tischler, interview with the author, May 3, 1995; Craig Covault, 'Shuttle Engine Delays Overcome,' ***Aviation Week and Space Technology*** (July 5, 1976), pp 43-49; James Thompson Jr, NASA, ***The Space Shuttle Main Engine and the Solid Rocket Booster*** (Alabama, NASA, Marshall Space Flight Center, Space Transportation System Briefing Series, No.3, October 14, 1980), p 4.

46 Lee Solid, interview with the author, July 26, 1995.

found.[47] Finally, Marshall/Rocketdyne were able to build dampers and bearings that counteracted the frequencies, but this solution was only suppose to be temporary, so that the engine could be tested at full power;[48] it ended up being the final solution.[49]

Although Marshall and Rocketdyne were behind schedule and had yet to test an engine at full power, by early 1977 many of the engine test milestones had been completed.[50] Nevertheless, the engine programme was to suffer another severe blow, when a test engine caught fire on March 24, 1977. Early analysis pointed towards a failure in the oxidizer turbopump. Programme officials believed that the fire had started in a section where dynamic seals separate the liquid oxygen in the pump from the hot gases in the turbine. A leak in the seals, argued Marshall, could have allowed the liquid oxygen and hot gases to mix, starting a fire. Minor changes to the seals were thus initiated.[51] A series of successful engine tests with the modified components after the fire appeared to substantiate the analysis and boosted the confidence of Marshall and

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47 Craig Covault, 'Shuttle Engine Delays Overcome,' ***Aviation Week and Space Technology*** (July 5, 1976), pp 43-49.

48 Lee Solid, interview with the author, July 26, 1995; Adelbert Tischler, interview with the author, May 3, 1995.

49 Adelbert Tischler, interview with the author, May 3, 1995.

50 'Shuttle Engine Passes Test Milestones,' ***Aviation Week and Space Technology*** (April 18, 1977), p 47.

51 'Shuttle Main Engine Being Modified,' ***Aviation Week and Space Technology*** (May 30, 1977), p 39.

Rocketdyne engineers.[52] But on September 8, 1977, an oxidizer turbopump exploded, dashing Marshall's hopes of achieving its goal of 10 000 seconds of test time by end of the year.[53]

Further research found that the flow of liquid oxygen coolant to the oxidizer turbopump bearings tended to unload built in stresses on one bearing in each pump, while adding extra loads to the second bearing in each pump.[54] Bearing problems in both the liquid hydrogen pump and the liquid oxygen pump plagued Marshall and Rocketdyne for several years.[55] Marshall sought assistance outside of the agency, but as James Kingsbury, Director of the Science and Engineering Directorate at Marshall, recollected, this was not forthcoming:

> We had bearing problems, we went all over the world asking people in the engine business what do you know about your bearings; and they said, well if we had yours we wouldn't do it that way, we'd quit.[56]

Marshall even went back to Pratt and Whitney, one of the engine design competitors, and asked it to review Rocketdyne's pump design. But what Pratt and Whitney

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52 'Engine Tests Raise Confidence,' ***Aviation Week and Space Technology*** (August 8, 1977), p 23.

53 Craig Covault, 'Shuttle Main Engine Problem Diagnosed,' ***Aviation Week and Space Technology*** (October 24, 1977), pp 17-20.

54 Craig Covault, 'Shuttle Main Engine Problem Diagnosed,' ***Aviation Week and Space Technology*** (October 24, 1977), pp 17-20.

55 Robert Lindstrom, interview with the author, August 17, 1995.

56 James Kingsbury, interview with the author, August 16, 1995.

proposed was a much heavier pump, which NASA would not take at that time because of its influence on overall system mass and, thus, payload lifting capability.[57]

Analysis indicated that bearing stress was caused by two major factors: the colossal speeds of the turbines and sharp increases in temperatures. Many areas of the pumps began super-cooled and then seconds later were subjected to temperatures of over 2 000 degrees fahrenheit. Marshall and Rocketdyne engineers, thus had to find a solution to a thermal gradient that appeared in their analysis graphs as just a spike.[58] Modifications involved a combination of changing the velocity of the coolant flow to the oxidizer turbopump bearings and applying different pre-load stresses to counteract propellant flow influences. The bearings in the main oxygen turbopump and its pre-burners were strengthened to carry loads 30 to 40 per cent higher than they were previously designed to withstand; and modifications were also made to the hydrogen turbopump bearings to ensure that they shared the loads more equally. In addition, the balance of the engine was also improved to reduce vibration and, therefore, the stresses that the bearings had to withstand during operation.[59]

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57 Robert Lindstrom, interview with the author, August 17, 1995.

58 Lee Solid, interview with the author, July 26, 1995; James Kingsbury, interview with the author, August 16, 1995.

59 Craig Covault, 'Shuttle Main Engine Problem Diagnosed,' ***Aviation Week and Space Technology*** (October 24, 1977), pp 17-20; Craig Covault, 'Modified Shuttle Engines Enter Testing,' ***Aviation Week and Space Technology*** (May 22, 1978), pp 55-61.

Many of the problems that afflicted the turbopump bearings also plagued the turbine blades within the hydrogen turbopump. The turbine is powered by hot gas (hydrogen rich steam) generated by the fuel pre-burner. The turbine blades thus went from the temperature of liquid hydrogen (minus 423 degrees fahrenheit) to the temperature of combustion (roughly 2 000 degrees fahrenheit) in about two and one half seconds; and because of the speed of the pumps (over 40 000 RPM), the turbine blades were very severely loaded. Testing towards full power revealed erosion of the turbine blades, which accelerated as the test continued.[60] In addition, a number of blades exhibited fatigue cracks (see figure 7:2), which gave rise to a major concern about blade failure, as Rocketdyne engineer, Lee Solid recalled:

> It was difficult for us to develop turbines. ... We had a period where we went through turbine blade cracks; and you really don't want a turbine blade coming off, [because] then [the turbine is] unbalanced and a pump can just go to destruction.[61]

Resolution of blade erosion and blade fatigue was approached in two ways. First, Marshall and Rocketdyne assumed that blade stress was a linear function of blade height, thus an attempt was made to modify the distribution

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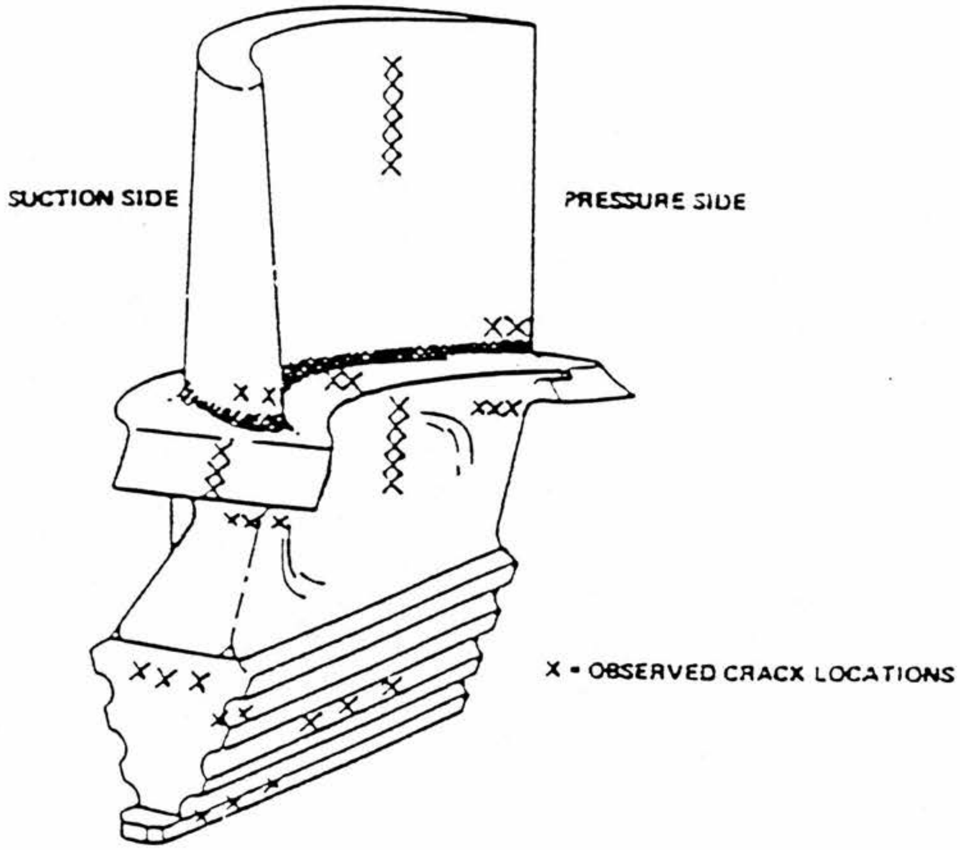
60 James Kingsbury, interview with the author, August 16, 1995; Lee Solid, interview with the author, July 26, 1995; Robert Ryan, Larry Salter, George Young, Paul Manafo, 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402; John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 600-617.

61 Lee Solid, interview with the author, July 26, 1995 .

Figure 7:2.



Source: John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1.***

of gases in the pre-burner. This, it was calculated, would reduce the inner-core temperature by raising the outer diameter temperature in a region where higher blade temperatures could be tolerated. Second, it was assumed that the temperature of the blades at ignition directly correlated with the amount of liquid oxygen accumulated up to the point of ignition. Marshall and Rocketdyne thus addressed the thermal gradient spike encountered at ignition by regulating the liquid oxygen flow to the pre-burner through an adjustment of the inlet valve. Further tests after these two modifications demonstrated a marked improvement in blade erosion and cracking, but the life of the blades were severely reduced; and NASA had to change its specifications, reducing blade life expectancy from the design goal of 27 000 seconds to 5 000 seconds.[62]

In a second report to the Congress, the National Research Council Assembly of Engineering's adhoc Committee for the Review of the Space Shuttle Main Engine Development Program, expressed concern over the performance and life expectancy of the hydrogen turbopump turbine blades. A major point of controversy between the Committee and Marshall/Rocketdyne focused on the location of fatigue cracks. Marshall and Rocketdyne had come to the conclusion that replacement of the turbine blades was only necessary

62 James Kingsbury, interview with the author, August 16, 1995; Lee Solid, interview with the author, July 26, 1995; Robert Ryan, Larry Salter, George Young, Paul Manafo, 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402; John McCarty, Byron Wood, 'Space Shuttle Main Engines: Interactive Design Challenges,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 600-617.

when cracks were found in the leading edge of the blades. Cracks that appeared on the blade's platform were considered to be tolerable unless they propagated into the blade's leading edge. The difficulty in knowing how far a crack had progressed formed a point of contention between NASA and the Committee. The committee considered that a procedure, which allowed the use of blades with small cracks in the platform for flight engines, was contrary to conventional practice; and it demanded that NASA detailed procedures for determining crack growth rates and developed statistical data to justify its confidence in blades with cracks in the platforms.[63]

On May 10, 1978, Marshall and Rocketdyne started a new series of tests with the modified engine. NASA hoped that the new series of tests would provide the engine programme with the momentum it needed to support a 1979 launch date. Nonetheless, apart from the significant hardware modifications required to get the engine to perform as "specified," Marshall and Rocketdyne were also faced with a lack of components to test. The limited components, originally procured with constrained funding to support engine development, were not able to keep pace with the changes in the programme. In addition, Marshall considered that the engine modifications could not be verified until

63 Craig Covault, 'Further Shuttle Launch Slip Forecast,' ***Aviation Week and Space Technology*** (February 26, 1979), pp 17-19.

the new components had accumulated 3 400 seconds of testing.[64]

May 1978 also witnessed the first cluster tests: the simultaneous firing of three engines together. The Main Propulsion Test Article, as it was known, consisted of a flight weight external tank attached to a test stand and a simulated orbiter. The upper two thirds of the simulated orbiter was a triangular beam that duplicated the orbiter's mass, but the aft of the simulator was nearly identical to a flight vehicle. Here the three main engines were mounted in the same arrangement as they would be on a flight orbiter (see Print 7:1). A key element of this test series was to test the manifold system and line arrangements of the propellant. Earlier human-rated boosters, like the Saturn 1B and the Saturn V, used multiple direct propellant lines instead of the overall manifold system designed for the shuttle. More than 300 Rocketdyne and NASA employees were directly involved in the tests series, which programme officials called the most complex large propulsion system evaluation ever undertaken in the US space programme. The test budget amounted to just over $52 million.[65]

NASA's upper management anticipated that with the start of these new tests its planned 1979 launch date could

64 Craig Covault, 'Modified Shuttle Engines Enter Testing,' ***Aviation Week and Space Technology*** (May 22, 1978), pp 55-61

65 Craig Covault, 'Propulsion Tests Provide Shuttle Data,' ***Aviation Week and Space Technology*** (May 29, 1978), pp 49-53.

Print 7:1

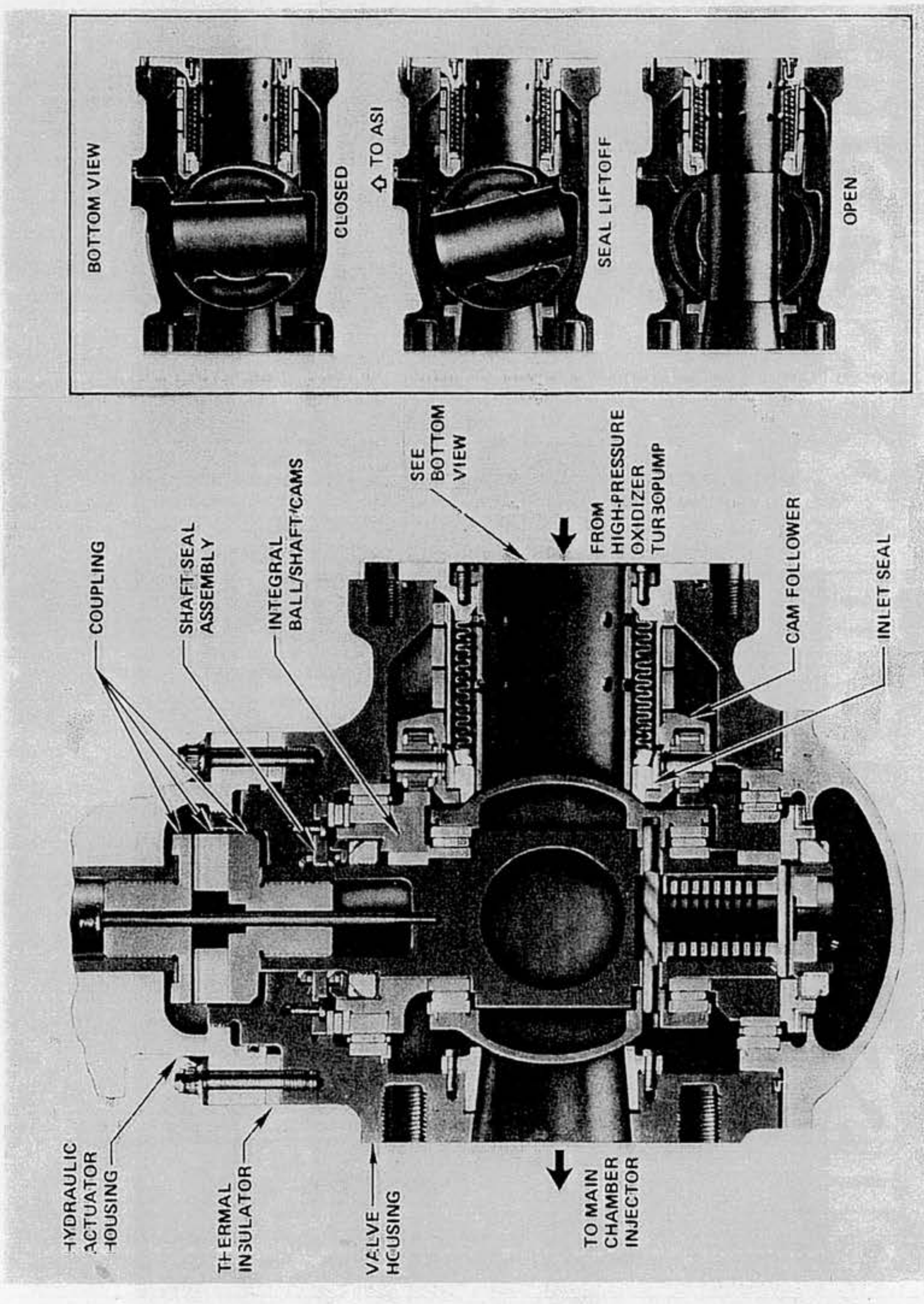
Source: Craig Covault, 'Propulsion Tests Provide Shuttle Data,' ***Aviation Week and Space Technology*** (May 29, 1978), pp 50, 51.

still be met. A series of successful firings through to September 1978, raised the confidence of NASA and Rocketdyne engineers enough for NASA's upper management to inform the Congress that all the design problems had been solved and that the engine would be able to support a first flight on September 28, 1979.[66] This view was overly optimistic. In December 1978, NASA faced a further setback as, once again, valve problems arose to plague engine development.

A failure in the engine's main oxidizer valve caused the destruction of yet another engine. The main oxidizer valve is a ball-type unit, in which the 2.5 inch diameter propellant passageway inside the metal sphere rotates about 90 degrees from the fully opened to the fully closed position. The valve is partially opened through a hydraulic servoactuator when the engine starts, to allow propellant to flow at a low power level. It is then gradually moved to the fully open position by the engine electronic controller as thrust increases. The main oxidizer valve regulates the flow of liquid oxygen from the oxidizer pump to the hydrogen and oxygen pre-burners and to the engine's main injector (see Print 7:2). It is an inherent part of the engine's staged combustion power cycle, where combustor gases are used to operate high-pressure turbopumps. The

66 John Yardley, statement for the record to the Subcommittee on Science, Technology and Space, February 22, 1978 (NASA History Office Archive, Washington DC); 'Shuttle Launch Delay,' ***Aviation Week and Space Technology*** (July 3, 1978), p 25; Craig Covault, 'Shuttle Engine Tests Successful,' ***Aviation Week and Space Technology*** (September 25, 1978), pp 12-13.

Print 7:2



Source: Edward Kolcum, 'Shuttle Engine Firing Successful,' ***Aviation Week and Space Technology*** (March 2, 1981), p 16.

first combustion stage occurs in the oxygen and hydrogen pre-burners. Exhaust from the pre-burners is then used to run turbines that power the high-pressure turbopumps that force hot, partially burned propellants into the main injector, where the propellants are enriched with oxygen. The second combustion stage then begins in the main chamber at higher temperatures and pressure levels.[67]

Turbulence, resulting from 5 000 pounds per square inch flow of liquid oxygen through the engine's main oxidizer valve, was thought to have caused vibration and rubbing among several valve components during the December test. A similar oxidizer valve was used on the Apollo J-2 engine, but the environment of the J-2 engine was less of a problem because the pressure flow through the valves was only about 2 000 pounds per square inch. Engine destruction was believed to be triggered when a sleeve, bolted to a spring housing in the inlet passage of the valve began moving and ignited a thin steel shim, which separates the sleeve from the housing.

Dom Sanchini, manager of the shuttle main engine programme for Rocketdyne, told *Aviation Week and Space Technology* that the fire in December 1978 was the result of a design problem rather than a problem in production or quality control:

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67 Craig Covault, 'Engine Failure Threatens Shuttle's Schedule,' ***Aviation Week and Space Technology*** (January 8, 1979), p 13; Bruce Smith, 'Shuttle Main Engine Tests Accelerated,' ***Aviation Week and Space Technology*** (February 12, 1979), p 44; 'Space Shuttle Engine Problems Believed Solved,' ***Aviation Week and Space Technology*** (April 16, 1979), p 19; 'Shuttle Valve Modifications To Be Made,' ***Aviation Week and Space Technology*** (August 20, 1979), p 21.

> We had a built-in tolerance in certain parts, which is quite common. What we will do now is design it so that the two parts are always press-fit together, no matter what the temperature or vibration environment.[68]

Modifications were thus made to the main oxidizer valve and two pre-burner oxidizer valves. The sleeve and spring housing was redesigned so the two parts fitted together tightly instead of having a small space between them. This involved increasing the thickness of the shim from 0.002 inches to 0.004 inches so it would be less likely to ignite. The sleeve mounting flange was also strengthened, so that more torque could be applied to the bolts that held it in place on the spring housing; and an application of dry lubricant on parts that may rub together and cause friction was added to engine fabrication procedures.[69]

The programme's biggest problem, as a result of the failure, was the time involved in the reconstructing the engine from a limited amount of parts and the time involved in retesting the valve. The valve failure had caused more than a month's delay to the engine programme; and when testing resumed the effort was stepped-up to evaluate a set of three redesigned oxidizer valves. The perceived verification time for the valves was two months. To speed up the process, Marshall and Rocketdyne tested the valves

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68 Dom Sanchini, quoted in Bruce Smith, 'Shuttle Main Engine Tests Accelerated,' ***Aviation Week and Space Technology*** (February 12, 1979), p 44.

69 Craig Covault, 'Engine Failure Threatens Shuttle's Schedule,' ***Aviation Week and Space Technology*** (January 8, 1979), p 13; Bruce Smith, 'Shuttle Main Engine Tests Accelerated,' ***Aviation Week and Space Technology*** (February 12, 1979), p 44; 'Space Shuttle Engine Problems Believed Solved,' ***Aviation Week and Space Technology*** (April 16, 1979), p 19; 'Shuttle Valve Modifications To Be Made,' ***Aviation Week and Space Technology*** (August 20, 1979), p 21.

on a rotated four day cycle. By early 1979, and after 5 000 seconds of test time, engine programme officials believed they had solved the main oxidizer valve vibration problem, because the tests showed no signs of a similar occurrence.[70]

By early 1979 the engine design had accumulated 34 810 seconds of testing time over 394 firings. NASA still believed that a first launch by the end of 1979 was possible. Nonetheless, the National Research Council's Assembly of Engineering follow-up report to Congress, disagreed with this assessment. The report, which was drafted before the main oxidizer valve failure, expressed the view that the engine's problems were likely to push the first shuttle launch well into 1980. The real concern for both Marshall and Rocketdyne was not however, problems of the past, but the difficulty in knowing what additional problems lay ahead.[71] In May 1979, one of them surfaced.

During a planned launch-duration (520 seconds) test on a flight certified engine, several of the more than 1 000 tubes that carry liquid hydrogen through the engine's exhaust nozzle to cool the engine bell, ruptured and separated from the nozzle (see figure 7:3).[72] Marshall and

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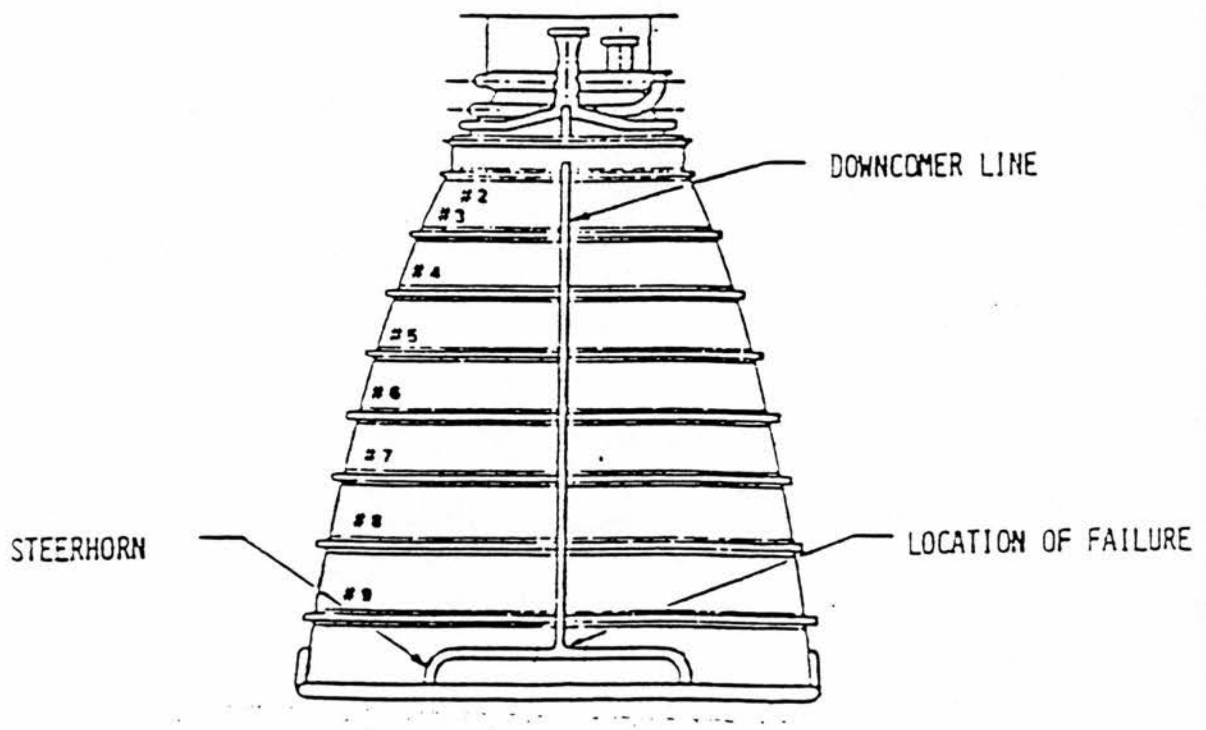
70 'Space Shuttle Engine Problems Believed Solved,' ***Aviation Week and Space Technology*** (April 16, 1979), p 19.

71 Craig Covault, 'Engine Failure Threatens Shuttle's Schedule,' ***Aviation Week and Space Technology*** (January 8, 1979), pp 12-14.

72 'Shuttle Three-Engine Test Article Firing Postponed,' ***Aviation Week and Space Technology*** (May 28, 1979), p 23.

Figure 7:3.



Source: Robert Ryan, Larry Salter, George Young, Munafo Paul. 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challange,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1.***

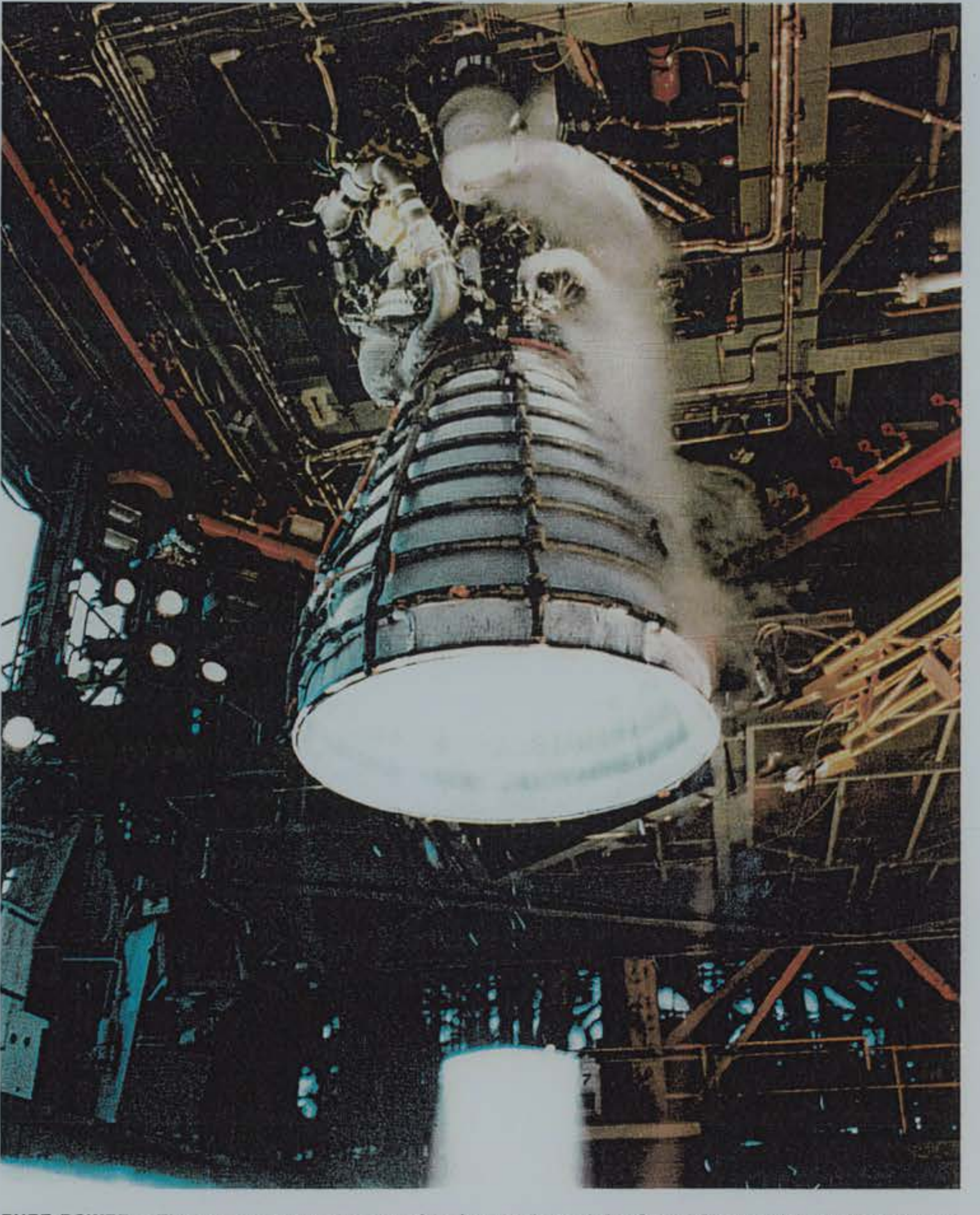
Rocketdyne engineers believed that flexing of the large flight nozzle over a series of 48 previous engine tests, which in turn applied pressure to the attached hydrogen fuel line, was the cause of nozzle failure.[73]

One of the problems involved in testing a high expansion ratio nozzle at sea level is atmospheric pressure. When pressure along the interior wall of the nozzle is less than the ambient air pressure, the nozzle flexes. This is because the exhaust plume does not fill the nozzle until internal pressure is greater than atmospheric pressure. As engine thrust builds up, two distinct phenomena occur. First, the plume is basically cylindrical in nature and is directionally unstable, moving around erratically within the nozzle. As the velocity of the plume flow increases, it passes through a region where a Mach disc or cone materializes within the nozzle and a void develops within the exhaust, known as a separation point. Then, as internal nozzle pressure increases, the Mach cone leaves the nozzle creating very high and localized shock waves (see Print 7:3 for engine during test). As a result of both these phenomena, sections of the shuttle engine's nozzle wall moved more than an inch and caused the normally circular outlet to become slightly elliptical in shape.[74]

73 Bruce Smith, 'Main Engine Incident Laid to Nozzle Flex,' ***Aviation Week and Space Technology*** (May 28, 1979), pp 77-79.

74 Lee Solid, interview with the author, July 26, 1995; Robert Ryan, Larry Salter, George Young, Paul Manafo, 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402; Bruce Smith, 'Main Engine Incident Laid to Nozzle Flex,' ***Aviation Week and Space Technology*** (May 28, 1979), pp 77-79; 'Main Engine Malfunctions Cause

Print 7:3



PURE POWER – The transparently clean combustion product of the Space Shuttle Main Engine's liquid oxygen and liquid hydrogen propellants is very evident during this static test conducted at the Santa Susana Field Laboratory of Rockwell International's Rocketdyne Division near Canoga Park, California. Rocketdyne is under contract to NASA's Marshall Space Flight Center in Alabama for the development and production of the Space Shuttle Main Engine.
RD-12/071188. Contact: Paul Sewell or Diana Croon White

Courtesy of Rocketdyne.

> We first found this out by accident, tearing up nozzles because of those loads and this separation point. ... So we designed ... one you could test at sea level and ran it almost full. I mean we pushed it right to the edge so you didn't have to go and build a highly sophisticated vacuum system to test rocket engines in.[75]

Two approaches were considered by programme officials to the nozzle flexing problem: first, redesign of the nozzle hydrogen duct system, to strengthen it against nozzle flexing; or second, redesign of the duct system to make it more flexible, so that the nozzle could adapt to shape changes. Marshall and Rocketdyne's attempts at the first solution found that a thickening of the tubes that carry liquid hydrogen through the engine's exhaust nozzle, only abetted the problem. The increased mass offset the increased stiffness thus the frequency of the shock loads stayed the same; increases in mass only increased the loads proportionally. A different solution thus had to be found. After further analysis it was determined that the horizontal run of the steerhorn had to be fixed to the rings that stiffen the nozzle, to reduce the shock waves. A device called a steam loop was also incorporated to reduce nozzle expansion induced by the high temperatures of the engines exhaust. Further tests corroborated the

Another Shuttle Launch Delay,' ***Aviation Week and Space Technology*** (November 12, 1979), p 20.

75 Lee Solid, interview with the author, July 26, 1995.

effectiveness of this design change and it was incorporated into the flight engine design.[76]

Notwithstanding, nozzle performance remained below hardware specifications. The nozzle had accumulated about 12 000 seconds of operation before failure, and although its design life was suppose to be 27 000 seconds, programme officials had to redetermine how many engine start-stop cycles would be acceptable for the large-nozzle design for future operations. The design goal of 55 firings could not be obtained, even with the redesign. A limit of 24 firings on each engine was eventually imposed on the nozzle design and the steerhorn feedline.[77]

A ruptured hydrogen fuel line returned to haunt NASA during a cluster test on November 4, 1979. The incident was similar to the failure that had occurred six months previously, but NASA officials claimed that the cause was very different. Investigation of the failure found that improper weld wire had been used in the fabrication of the engines. Marshall and Rocketdyne discovered over 1 900 welds in each engine where the wrong weld wire had been used, 400 of which were considered critical. Amplifying the problem, suspect welds were also found on the flight

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76 Lee Solid, interview with the author, July 26, 1995; Robert Ryan, Larry Salter, George Young, Paul Manafo, 'SSME Lifetime Prediction and Verification, Integrating Environments, Structures, Materials: The Challenge,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 386-402; Bruce Smith, 'Main Engine Incident Laid to Nozzle Flex,' ***Aviation Week and Space Technology*** (May 28, 1979), pp 77-79; 'Main Engine Malfunctions Cause Another Shuttle Launch Delay,' ***Aviation Week and Space Technology*** (November 12, 1979), p 20.

77 Bruce Smith, 'Main Engine Incident Laid to Nozzle Flex,' ***Aviation Week and Space Technology*** (May 28, 1979), pp 77-79; 'Main Engine Malfunctions Cause Another Shuttle Launch Delay,' ***Aviation Week and Space Technology*** (November 12, 1979), p 20.

engines fitted to Columbia, which had to be pulled off the vehicle for repair. Repair consisted of the application of nickel plating to the weld. But, first, an acid etch test had to be used to determine if the suspect welds were indeed below specifications. During the tests and repair process, Marshall and Rocketdyne found that over 20 per cent of the welds in each engine consisted of Inconel 600, a weaker wire than the specified Inconel 718. Over 110 hours of plating was thus deemed necessary for each engine. The problem was further complicated by the location of many of the welds; deep inside the turbopump machinery.[78]

In mid-1980 another serious fabrication problem was unearthed. By chance a contractor who inspected the engine's heat exchangers picked one up in an improper manner and accidently bent it. When attempts were made to straighten the bend, the exchanger cracked; a reaction that should not have occurred.[79]

The heat exchanger is an engine component that converts liquid oxygen into gaseous oxygen. The component had failed before, back in December 1978, causing a fire on the test stand. The National Research Council Assembly of Engineering's adhoc Committee for the Review of the Space Shuttle Main Engine Development Program, thought the heat

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78 'Main Engine Malfunctions Cause Another Shuttle Launch Delay,' ***Aviation Week and Space Technology*** (November 12, 1979), p 20; Craig Covault, 'Shuttle Project Faces New Problems,' ***Aviation Week and Space Technology*** (December 10, 1979), pp 20-21.

79 Craig Covault, 'Shuttle Concerns Force Action,' ***Aviation Week and Space Technology*** (June 2, 1980), pp 14-16.

exchanger posed a potential threat to the total shuttle system and were concerned about the incident. A destructive failure of the heat exchanger during flight could potentially result in the loss of the entire shuttle.[80]

Nonetheless, Rocketdyne and Marshall were having a great deal of difficulty in determining the cause of the failure; as Dom Sanchini, manager of the shuttle main engine programme for Rocketdyne, told *Aviation Week and Space Technology*:

> We haven't been able to find anything wrong from a design standpoint. We have to suspect and generally believe that somehow the problem existed in the fabrication process or in some retrofits we did to that area of the engine that somehow damaged the heat exchanger. Work was done in the area of the heat exchanger, but not on the heat exchanger itself, so there was no requirement to specifically proof test the heat exchanger after the work.[81]

Engineers at Rocketdyne had been trying to simulate damage to a heat exchanger to see if a leak, that the company believed caused the December 1978 fire, could be duplicated. None of these damage tests, however, resulted in any leaks. Nevertheless, the incident in 1980 highlighted a possible cause. During the inquiry into why the heat exchanger cracked after restraightening, Rocketdyne found that improper material had been used in the manufacture of some of the heat exchangers. The device

80 Craig Covault, 'Engine Failure Threatens Shuttle's Schedule,' ***Aviation Week and Space Technology*** (January 8, 1979), pp 12-14.

81 Dom Sanchini, quoted in Craig Covault, 'Engine Failure Threatens Shuttle's Schedule,' ***Aviation Week and Space Technology*** (January 8, 1979), p 14.

was suppose to be made entirely of 316 stainless steel, but Rocketdyne found that a 718 nickel alloy had been used on the heat exchanger under investigation. As the inquiry expanded, Rocketdyne detected two more engines which also contained the improper metal.[82]

Nevertheless, the engine tests continued, under the weight of NASA's upper management pressure to keep the March 1981 launch date. But on July 30, 1980 yet another engine caught fire on the test stand. A post-test analysis of the fire indicated that it was caused by a failure of a sensor system, which fed information to the engine's computer controller. For the engine's computer controller to make accurate "decisions", it monitors the pressure inside the engine's main combustion chamber. But, since the gas in the chamber was hotter than any pressure sensor could tolerate, the sensor had to be placed in a tube off to one side of the main combustion chamber and then continually cooled by a flow of liquid hydrogen. Marshall/Rocketdyne's early analysis found that an inlet mechanism, which regulated the flow of hydrogen to the sensor failed, thus, permitting a higher than required flow of hydrogen over the sensor. This resulted in the senor receiving incorrect information about what was going on inside the combustion chamber, so in turn it fed

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82 Craig Covault, 'Engine Failure Threatens Shuttle's Schedule,' ***Aviation Week and Space Technology*** (January 8, 1979), pp 12-14; Craig Covault, 'Shuttle Concerns Force Action,' ***Aviation Week and Space Technology*** (June 2, 1980), pp 14-16.

disinformation to the computer controller, which then drove the engine beyond specifications.[83]

By the end of 1980 Marshall and Rocketdyne had completed several engine tests with no problems. The programmes initial goal of 60 000 seconds of pre-flight test-stand firing had been well overtaken because of the additional tests required to qualify all the modifications: NASA had accumulated just over 80 000 seconds. However, NASA original goal of running an engine for 27 000 seconds before major refurbishment had been reduced to around 15 000 seconds. And in many areas, such as the turbopumps this was even less. Nonetheless, the engine worked and the technology was ready for the "real test", the first flight.[84]

Fabrication and Modification: the External Tank.

As the design of the shuttle's external tank was based on the Saturn tanks, development was judged by many at NASA as not to pose any major technological challenges.[85] Notwithstanding, the external tank did present NASA with a number of problems. Interactions with other elements of the

83 Craig Covault, 'NASA Tightens Shuttle Schedule Again,' ***Aviation Week and Space Technology*** (August 11, 1980), pp 27-28.

84 'Shuttle Engine, Tile Work Proceeding on Schedule,' ***Aviation Week and Space Technology*** (September 15, 1980), p 26; 'Final Shuttle Engine Tests Set,' ***Aviation Week and Space Technology*** (October 27, 1980), p 53; Edward Kolcum, 'Shuttle Engine Firing Successful,' ***Aviation Week and Space Technology*** (March 2, 1981), pp 17-19.

85 James Kingsbury, interview with the author, August 16, 1995.

shuttle system, its operational environment and political matters all coalesced to remodel and refine the shape of the external tank as its development proceeded. By mid-1974 it became increasingly clear that not all the design details had been sufficiently scrutinized.

Since both the propellants are cryogenic (liquid oxygen, at minus 297 degrees fahrenheit and liquid hydrogen, at minus 423 degrees fahrenheit), ice would form on the outside of the external tank during propellant loading and prior to lift-off. This phenomena was, of course, well know to NASA. Previous experience with cryogenic technologies on the Saturn launch vehicle and the Apollo spacecraft had furnished the agency with a broad knowledge base about the properties of cryogenic fuels. The major problem at that time was the construction of a suitable environment that would limit propellant boiloff so as to maintain the fuel's quality. Minor ice build up on the rocket's external structure was not, in itself, considered to be a real problem. Yet, on the shuttle, such occurrence could potentially be very dangerous.

The orbiter's thermal protection system, a ceramic tile being developed by the Ames Research Center and Lockheed, was proving very fragile. It was notified that if ice was allowed to form on the external tank then debris caused by the vibration of lift-off could damage this system. So, by April 1974, a 'no ice/debris' requirement was imposed.[86]

> We were well into the design of the tank when we realized just how fragile the insulation on the bottom of the orbiter was going to be. So then we had to come up then with insulation on the tank that would withstand less than minus 400 degrees [fahrenheit] on one side and still be above 32 degrees [fahrenheit] on the outside so as not to create ice.[87]

No ice meant that both Marshall and Martin Marietta had to design a thermal system that would cover the entire acreage of the tank, including all its feed lines, brackets and anything else that was on the outside.[88]

During April 1974, several working sessions took place to evaluate various solutions to the icing problem. A number of proposals were put forward, ranging from de-icing sprays to thermal paints and heating blankets, or shrouds.[89] As these differing approaches dwindled the concept of a spray-on-foam, which could cover the entire tank, including all the brackets and feed lines, dominated.[90] Spray-on-foams had been used on the Apollo/Saturn vehicles as cryogenic tank insulators to

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86 James Odem, interview with the author, August 21, 1995; Frederick Bachtel, Jerold Vaniman, James Stucey, Carroll Cray, Bernard Widofsky, 'Thermal Design of the Space Shuttle External Tank,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Vol 2*** pp 1041-1050.

87 James Odem, interview with the author, August 21, 1995.

88 ***Ibid.***

89 R.H. Gray, memorandum for distribution, May 7, 1974 (Kennedy Space Center Archive, Florida).

90 Frederick Bachtel, Jerold Vaniman, James Stucey, Carroll Cray, Bernard Widofsky, 'Thermal Design of the Space Shuttle External Tank,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Vol 2*** pp 1041-1050.

prevent propellant boiloff. A rigid closed cell polyurethane foam, specified as BX-250, had been employed on the second stage of the Saturn rocket and had also had some commercial success. BX-250, a low density material, proved to have excellent insulation qualities at low temperatures and was available on the commercial market.[91] Accordingly, in June 1974, NASA selected the BX-250 spray-on-foam as the external tank's thermal insulation design.[92]

Notwithstanding its advantages, by the end of 1974 the acceptability of BX-250 was in serious doubt. During ascent, the leading edge of the tank would have to withstand aerodynamic heating. In the area between the orbiter and the tank very high and contained velocities of air could also cause aerodynamic heating.

> The insulation had to both insulate from a ice standpoint, but it had to withstand very high temperatures also. So those two are two absolutely opposing requirements, we ... literally [had to] develop very light foam insulations that could withstand both aerodynamic heating as well as being a good [cryogenic] insulator.[93]

To solve these problems, Martin Marietta had initially proposed the direct application of an ablator material, SLA-561, to the cryogenic substrate at points where high temperatures were expected; the tank's leading edge, the

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91 James Odem, interview with the author, August 21, 1995; Frederick Bachtel, Jerold Vaniman, James Stucey, Carroll Cray, Bernard Widofsky, 'Thermal Design of the Space Shuttle External Tank,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Vol 2*** pp 1041-1050.

92 Letter from Robert Thompson to Shuttle Projects Office Manager, Kennedy, November 4, 1974 (Kennedy Space Center Archive, Florida).

93 James Odem, interview with the author, August 21, 1995.

intertank and the aft dome. Wind tunnel tests conducted throughout 1974, however, were showing large increases in predicted ascent heating, which exceeded the capabilities of BX-250. The system was thus unable to accommodate the new environment without major increases in the use of the SLA-561 ablator, which resulted in a significant and unacceptable increase in mass.[94] Space Shuttle Manager, Robert Thompson ordered the NASA Centers to find an alternative solution.[95]

In November 1974 a new urethane modified isocyanurate foam material produced by the UpJohn Company, CPR-421, was selected to replace the BX-250.[96] This material possessed the required ablation characteristics, was compatible with the original design concept and was also commercially available. There was, nonetheless, concern over its suitability. The material was going to be used in an environment which was unlike any previous commercial one so it would require considerably greater quality controls for flight qualification. A comprehensive developmental and verification programme was, therefore, initiated to

94 James Odem, interview with the author, August 21, 1995; Frederick Bachtel, Jerold Vaniman, James Stucey, Carroll Cray, Bernard Widofsky, 'Thermal Design of the Space Shuttle External Tank,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Vol 2*** pp 1041-1050.

95 Letter from Robert Thompson to Shuttle Projects Office Manager, Kennedy, November 4, 1974 (Kennedy Space Center Archive, Florida).

96 Committee on Science and Technology US House of Representatives, ***Space Shuttle: 1975 Status Report*** (Washington, US Government Printing Office, February 1975), p 94.

characterize this "off the shelf" product, which lasted into 1975.[97]

Towards the end of 1975, Martin Marietta was forced to stop work on all CPR-421 activity because of two toxicity problems, which by that point had become critical. The first concerned its application; because of the isocyanates used, the urethane foam was potentially hazardous to personnel working with the material. It was found that exposure to CPR-421 during application could cause respiratory problems and was potentially lethal. The second problem revolved around a ominous chemical reaction that could occur when the external tank reentered the atmosphere. Tests at the Southern Research Institute, conducted during January 1976, confirmed an earlier discovery that the CPR-421 foam contained chemical components which could, on pyrolysis, produce a toxic substance referred to as trimethylol propanephosphate.[98]

There were some within NASA who argued that pyrolysis on reentry did not present a problem, as it could be assumed that the Earth's atmosphere would 'dilute the products of combustion tremendously.'[99] Nevertheless, a programme to reformulate a new composition, which did not

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97 Frederick Bachtel, Jerold Vaniman, James Stucey, Carroll Cray, Bernard Widofsky, 'Thermal Design of the Space Shuttle External Tank,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Vol 2*** pp 1041-1050; Committee on Science and Technology, US House of Representatives, ***Space Shuttle: 1976 Status Report*** (Washington, US Government Printing Office, October 1975), pp 174-175.

98 NASA position paper, n.d (Kennedy Space Center Archive, Florida).

99 ***Ibid.*** p 2.

contain the phosphate component was initiated; resulting in the manufacture and testing of a new material, designated CPR-488.

Solutions to the first problem involved the establishment of strict production and application techniques. Facilities had to be designed to ensure there was no release of any toxic products outside of the spray enclosure. An automatic, computer controlled system was therefore employed to control and monitor spray application, which had to be conducted inside large environmentally-controlled application cells.[100]

Health and safety were not the only concerns with foam application. Insulation efficiency and ablator rates had to be consistent and repeatable. The most critical defect, which had to be controlled and was also difficult to detect, was a weak bond-line. It was discovered that under cryogenic conditions there was an increased risk that the insulation may de-bond because the materials became brittle at approximately minus 180 degrees fahrenheit. Material temperature at application, thus had to be heated to near 135 degrees fahrenheit and tank substrate temperature had to be heated to 140 degrees fahrenheit to ensure adhesion. This critical process did not however, alleviate the risk of de-bonding during fuelling. Two primary strains could

100 ***Ibid;*** Frederick Bachtel, Jerold Vaniman, James Stucey, Carroll Cray, Bernard Widofsky, 'Thermal Design of the Space Shuttle External Tank,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Vol 2*** pp 1041-1050.

adversely effect the insulation materials during tank loading; cryogenic chill-down of the tank (thermal strain) and internal tank pressure (substrate strain). Traditional practice was to load cryogenic fuel tanks with little or no ullage pressure. The tanks were subsequently pressurized for launch and ascent to meet both structural and propellant delivery requirements. Tests and analysis showed that if the strain due to tank pressurization is applied prior to loading, when the materials were near to room temperature, rather than cryogenic, then their structural margin was increased.[101]

Problems with the insulation materials was not the only difficulty facing NASA. As Herb Yarbrough, member of the Space Shuttle Program Office at JSC, recalled, the structural integrity of the liquid oxygen tank was also causing problems:

> We found out that the ... oxygen tank couldn't be fuelled without pressure. We used water to simulate the liquid oxygen and when they pumped water into the tank without a head of pressure on the tank the dome of the tank kind of collapsed and left a inward dent in the tank which was about 18 inches wide and about 18 inches deep and about 12 feet long. So they found out that they had to keep the tank pressurized as they were filling it with liquid oxygen.[102]

A re-ordering of the launch procedures was, therefore, initiated and both the liquid oxygen and the liquid

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101 *Ibid.*

102 Herb Yarbrough, interview with the author, September 5, 1995

hydrogen tanks were to be pressurized prior to fuel loading.

In March 1976 engineers at Johnson unearthed a "bombshell". Detailed investigations determined that using the orbiter as the backbone of the entire shuttle structure would not be workable because it would be unable tolerate the high wind loads of ascent.[103] Consequently, a fundamental problem arose; either Johnson would have to redesign the orbiter, or Marshall would have to redesign the external tank. Johnson, as the controlling Center, was responsible for making the decision and when it designated the tank, a political altercation transpired between Marshall and Johnson. In terms of systems integration, the problem represented a serious violation of interface protocols. Some at Marshall regarded the problem as Johnson's and thus up to Johnson to correct. Passing it onto Marshall was perceived as a misuse of Johnson's power. As James Kingsbury, Director of the Science and Engineering Directorate at Marshall, recollected however, the decision was really driven by cost. At such a late stage in the shuttle's development it was far simpler and cheaper, to

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103 James Kingsbury, interview with the author, August 16, 1995; GAO, ***Space Transportation Systems: Past, Present, Future*** Report to the Congress, May 27, 1977 (General Accounting Office Distribution Center, Washington DC), pp 9-10.

redesign the external tank than it was to redesign the orbiter.[104]

> So the decision was made to redesign the attach points to the tank to take the loads out through the tank. The tank was not designed to take the loads out, so the tank had to be redesigned.[105]

Understanding the wind conditions and what wind conditions the shuttle could withstand, placed an atypical demand on NASA's dynamic load analysts. Whereas all NASA's previous launch vehicle configurations were axisymmetric, the shuttle had four bodies connected in parallel. Definition of the forces and pressure distributions on all the bodies was thus extremely complex. The most crucial event during ascent would be when the shuttle flew through the Max-Q, the time of maximum dynamic pressure (forces greater than 400 pounds per square foot).[106]

> The tank at that point in time is still the back bone, holding it all together. So you've got the solid rocket's thrust, that's going in at the middle of the inner tank and you got the orbiter thrust, that's going in at the back end of the liquid hydrogen tank. So you're pushing about a million and half pounds of [liquid oxygen] up there and yet you've got a long liquid hydrogen tank that's real light ... yet its got to take all of the loads from the [main engines]. So its a very tricky design in dynamics analysis that we had to prove on the ground before we flew it for the first time.[107]

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104 James Kingsbury, interview with the author, August 16, 1995.

105 James Kingsbury, interview with the author, August 16, 1995.

106 James Odem, interview with the author, August 21, 1995; Alden Mackey, Ralph Gatto, 'Structural Load Challenges During Space Shuttle Development,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** pp 335-344.

107 James Odem, interview with the author, August 21, 1995.

Early load studies consisted of full dynamic simulations and cases were run using typical techniques to survey loads. It soon became apparent, however, that the shuttle's configuration was far more sensitive to wind conditions and system dispersions than was previously realized. A continuation with the traditional method would have been both expensive and time consuming. New analytical tools, therefore, had to be developed to provide a more rapid and cost-effective method of surveying all of the combinations of flight time, wind conditions and systems dispersions.[108]

A redesign of the external tank to strengthen its structure, so that it could act as the backbone of the shuttle system, was initiated, primarily because of the increases in the predicted aerodynamic loads. Nonetheless, a new problem surfaced in early 1977, which gave further cause to reinforce the external tank. An update to the lift-off analysis database, conducted to support the 1977 shuttle critical design review, indicated a marked increase in dynamic loads at the region of the orbiter/external tank forward attachment structure. It was discovered that during the fire up start sequence, as the orbiter's main engines built up to 100 percent power level, the force of the

108 The focus of the load survey was the q-alpha versus q-beta flight envelopes called "squatcheloids." The squatcheloid provided a means of defining the pertinent flight dynamics parameters such as dynamic pressure (q), angle of attack (alpha), angle of sideslip (beta) and the rotational accelerations. Alden Mackey, Ralph Gatto, 'Structural Load Challenges During Space Shuttle Development,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** p 340.

combined engine/booster thrust would bend the top of the external tank.[109]

> The top of [the tank would] move about four feet. [When] you fire up the solids and when they come up [to] thrust, you want the tank to be back straight so that when you lift off all of the vehicles are in the right attitude and that's a pretty sensitive sequence. What that meant was we had to understand extremely well the structural dynamics, the structural capabilities of that tank.[110]

An extensive structural test programme was thus initiated on the external tank. A complicating factor was that NASA had selected construction materials that got stronger at the cryogenic temperatures. In order to verify the capabilities of the external tank, therefore, Marshall had to run the qualification tests at those cryogenic temperatures.[111] As External Tank Manager, James Odem recalled, testing a tank filled with a quarter of a million pounds of hydrogen was a harrowing experience.

> I lost a lot of nights sleep running that test program because any leak or any slight failure and you lose the whole facility.[112]

Reinforcement of the external tank alone did not represent a total solution to the problem. Hence, several additional options were also examined including: reducing

109 James Odem, interview with the author, August 21, 1995; Herb Yarbrough, interview with the author, September 5, 1995; Alden Mackey, Ralph Gatto, 'Structural Load Challenges During Space Shuttle Development,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** pp 336-339.

110 James Odem, interview with the author, August 21, 1995.

111 James Odem, interview with the author, August 21, 1995.

112 James Odem, interview with the author, August 21, 1995.

the main engine thrust on lift-off; lift-off with only two of the three main engines; tilting the shuttle on the launch pad; and introducing a time delay for the solid rocket boosters ignition and vehicle release. NASA concluded that most of these options were either ineffective, unfeasible, or introduced an undesirable risk to safety. Only the last, introducing a time delay on booster ignition, appeared to be both effective, easy to implement and fall within acceptable risk criteria. A team was thus established to calculate the dynamics of shock and vibration on the shuttle during engine ignition and plot a time history of the base-bending moment. Mathematical models indicated that a delay of 2.7 seconds should be specified before booster ignition. Herb Yarbrough, member of the Space Shuttle Program Office at JSC, witnessed the first real test of these calculations during a flight readiness test of the main engines in 1980:

> I recall being amazed with results ... from ... the activity that calculated when to light the solid rocket boosters ... It turned out we did a flight readiness firing before we actually flew the vehicle. [We] lit up the main engines and burned them for 20 seconds ... and in that time we found out that [the] calculations were right on the money. ... The vehicle would bend and ... sway in each direction and [they] calculated the frequency of that sway and when we should light the solid rocket motors.[113]

Yet despite all its problems the first external tank rolled off the production line in early 1978, ready for a

113 Herb Yarbrough, interview with the author, September 5, 1995

1979 launch. On its arrival at Kennedy the giant tank drew quite a crowd (see print 7:4).

Testing and Model Development: Thermal Protection.

The Thermal Protection Branch at NASA's Ames Research Center had been researching and testing reusable thermal protection materials since the mid-1960s. By 1970 this programme had been stepped up, as Ames conducted tests on candidate insulation materials for the shuttle. During these tests, two problems had become evident. First, facilities were found to be inadequate for accurate testing. The arc-jets at Ames, while able to produce the necessary high-temperatures, were incapable of sustained tests on large samples of heat shield materials; and second, because facilities at Ames were deemed inadequate, the Thermal Protection Branch considered that the results of the tests could not be analyzed satisfactorily. Sufficient knowledge about the properties of the materials, it was argued, could not be gleaned from the tests being conducted. Underlying the arguments coming from the Thermal Protection Branch in 1970 were proposals for expansion. Larger facilities and more researches would serve to both understand the heating phenomenon Ames was dealing with, and demarcate the work of Ames from its main internal competitor, the Langley Research Center.[114]

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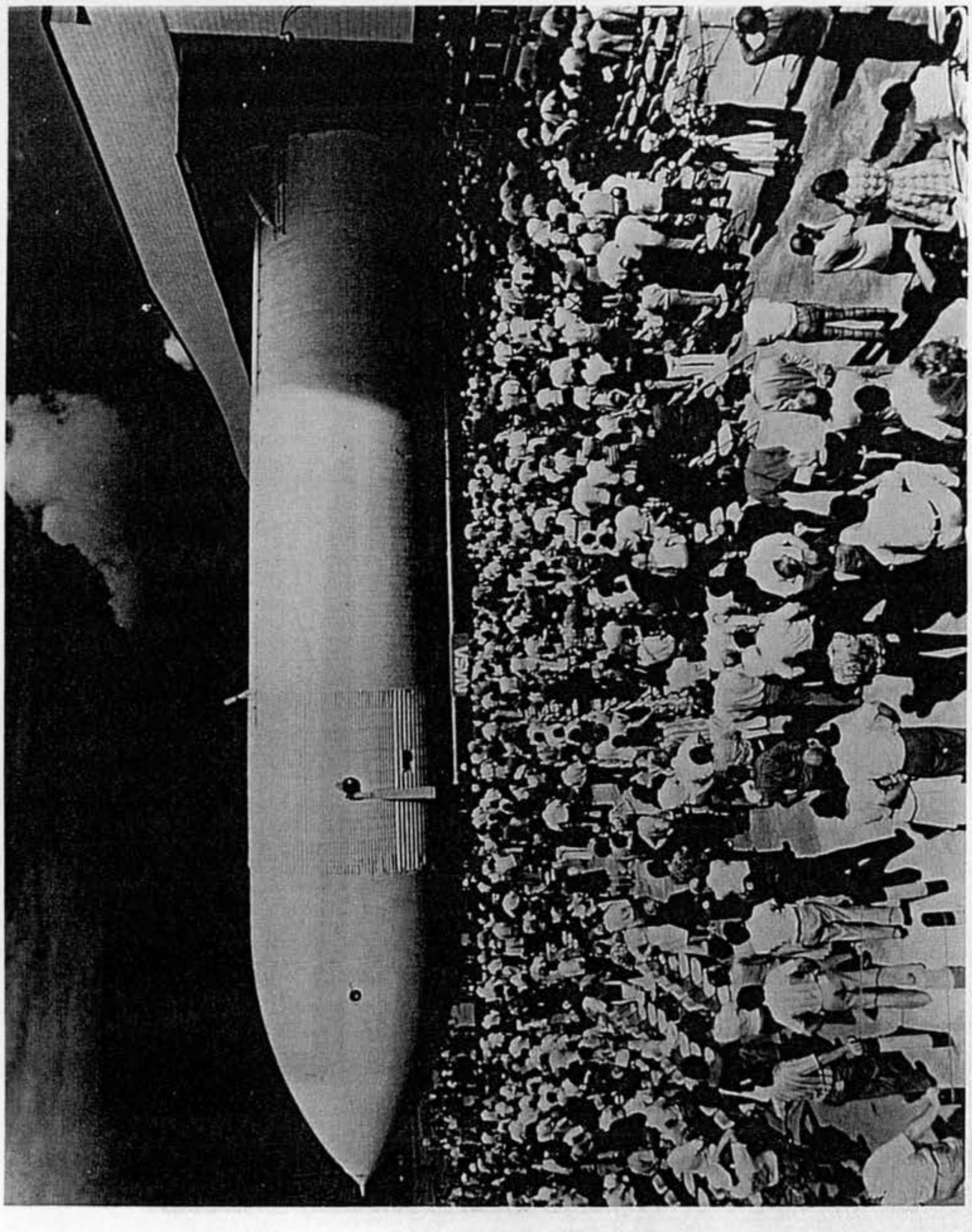
114 Elizabeth Muenger, ***Searching the Horizon: A History of Ames Research Center*** (Washington DC, NASA, Scientific and Technical Information Branch, 1985), pp 168-173.

Print 7:4



Courtesy of NASA.

In April 1975 Ames's new 60 megawatt arc-jet facility was put into operation. Three times as powerful as any previous facility, its primary task over the next few years would be to test the heat resistance of the orbiter's thermal protection system. Although the verification test programme had yet to be fully defined, it was considered that materials characterization would involve classic multiple tests to answer questions pertaining to life expectancy. The Office of Manned Space Flight's requirements had dictated that thermal protection material samples should be subjected to 100 tests of 1 000 seconds each. In addition, tests would focus on heating the materials up to 2 500 degrees fahrenheit and then raising the temperature in increments of 100 degrees fahrenheit until destruction.[115] Although important, these tests provided only a limited interpretation of the environment within which the thermal protection system would operate. NASA and Lockheed engineers had to go much further. If the shuttle was to come back unscathed, all reentry conditions had to be duplicated and known as accurately as possible.

Reentry heating phenomena had been under investigation since the mid-1920s,[116] but the first steps towards a quantitative understanding of reentry dynamics was not

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115 Benjamin Elson, 'New Unit to Test Shuttle Thermal Guard,' ***Aviation Week and Space Technology*** (March 31, 1975), p 52.

116 Walter Hohmann had published work in 1925 on the theoretical mechanics of a reentry vehicle. For more detail see Richard Hallion, ***The Path to the Space Shuttle: The Evolution of Lifting Reentry Technology.*** (History Office, Air Force Flight Test Center, November 1983); Dennis Jenkins, ***Space Shuttle*** Chapter 1.

established until the late-1950s. Advancements in supersonic flight and reentry ballistic missile technology, during the 1950s, rested upon a major shift in aerodynamic theory. Within these new environments, the characteristics of fluid dynamics changed. Fluid flow had to be viewed as compressible as opposed to incompressible, which was the case for subsonic aerodynamics. Aerodynamic engineers, thus had to delve deeper into the physics and the chemistry of gases to deal with the new problems posed by reentry and supersonic flight. Kinetic theory of gases, flow problems and radiation transfer all moved to centre stage. Classical aerodynamic boundary-layer theory had long dictated that streamline needle-nose shapes were required to reduce aerodynamic drag and, thus, minimize heat transfer to the vehicle's structure. Aerodynamicists at the National Advisory Committee for Aeronautics, however, presented the radical idea in 1951, that reentry shapes needed to be blunt. Blunt shapes, it was discovered, deflected more heat into the air; and because the vehicle's resistance to the tenuous upper atmosphere would be at its maximum, the vehicle would start to slow down sooner within the thinner atmosphere so less heat would be transferred to the vehicle's surface.[117]

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117 Walter Vincenti, workshop presentation at the University of Edinburgh, May 20, 1998; Robert Ried, 'Orbiter Entry Aerothermodynamics,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2*** pp 1051-1061; Benjamin Elson, New Unit to Test Shuttle Thermal Guard,' ***Aviation Week and Space Technology*** (March 31, 1975), p 52. Jerry Grey, ***Enterprise*** pp 103-105; David Halliday, Robert Resnik, ***Physics: Parts 1 and 2*** (New York, John Wiley & Sons, Third Edition, 1978), Chapter 18.

During the 1960s the reentry dynamics of blunt-nose vehicle configurations had been well practised by aerodynamicists working on the Mercury, Gemini and Apollo capsules. Nevertheless, requirements for the orbiter's thermal protection system dictated a more accurate and intricate definition of reentry heating than for any of NASA's previous vehicles. The three dimensional geometric complexity and the large scale of the orbiter posed a greater challenge to the definition of the reentry flow-field and subsequent heating, than had any previous system.[118] Simulating flows, especially turbulent flow, in the laboratory presented NASA and Lockheed with their most difficult problem. Although the science of fluid mechanics was still largely unknown territory,[119] its understanding was of great importance, because maximum heating rates and material ablation would occur when turbulent flow became fully established.[120]

> The phenomena of turbulent flow and boundary-layer transition have been under intense investigation for more than a century with somewhat limited success. This limitation is possibly measured by the anxiety which develops when engineers are required to predict boundary-

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118 Robert Ried, 'Orbiter Entry Aerothermodynamics,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2*** pp 1051-1061.

119 Stanley Berger, ***Laminar Wakes*** (New York, American Elsevier Publishing Co Inc, 1971), preface.

120 Benjamin Elson, New Unit to Test Shuttle Thermal Guard,' ***Aviation Week and Space Technology*** (March 31, 1975), p 52.

layer transition outside the range of experimental data.[121]

In general there are two types of boundary layers, laminar and turbulent; and both are fundamentally different in character. Laminar flow takes place smoothly in parallel laminae, free of irregular eddying motion. Turbulent flow, by contrast, contains a large number of small eddies that move in a chaotic manner. As a result of the transverse mixing of gases, turbulent flow tends to be thicker than laminar flow and has higher velocities close to the surface. This effect causes the turbulent flow (all things being equal) to exert higher skin friction than the laminar flow and, therefore, cause extreme surface heating.[122]

The problem of simulating turbulent flows and boundary-layer transition was tackled through the development of both simplified theoretical models and empirical evidence based on the previous experience and knowledge gleaned from the blunt reentry capsules of Mercury, Gemini and Apollo.[123] This could be done because geometrically similar bodies develop identical flow and shock patterns within the subsonic and supersonic speed regimes. Within the hypersonic speed regime, however, there is considerable interaction between the boundary-layer and

121 Robert Ried, 'Orbiter Entry Aerothermodynamics,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2*** p 1055.

122 Walter Vincenti, ***What Engineers Know and How They Know It*** pp 37-39.

123 Robert Ried, 'Orbiter Entry Aerothermodynamics,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2*** pp 1051-1061.

the shock pattern. When this occurs, the similitude requirements are more difficult to satisfy. To circumvent this problem the standard technique was to introduce simplified models using data from accurate predictions under incompressible flow conditions to provide predictions under compressible flow conditions using distortions of geometry to balance distortions of velocity.[124] Representative locations were thus selected on the orbiter and then data collected from tests on models in a wind tunnel were scaled-up to flight conditions by correlating boundary-layer transition and turbulent heating as a function of the Reynolds number behind a normal shock (see figure 7:4).[125] From these simplified models a reentry trajectory was mapped that would be consistent with the thermal protection system's capabilities.[126] The orbiter's reentry configuration, however, was not a true blunt reentry vehicle nor was it a slender flight vehicle. The flow dynamics would vary along the orbiter from the high entropy of a blunt-body nose flow asymptotically toward a low entropy slender-body flow.[127] More complex models and analytical techniques were, therefore, required.

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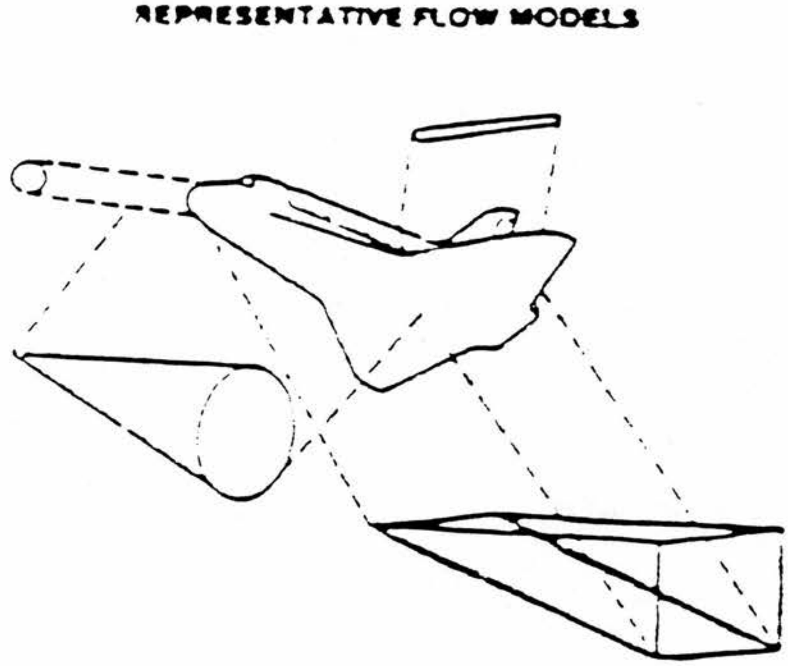
124 Stanley Berger, ***Laminar Wakes*** preface, pp 3-6.

125 Robert Ried, 'Orbiter Entry Aerothermodynamics,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2*** pp 1051-1061.

126 B. Kent Joosten, 'Descent Guidance and Mission Planning for the Space Shuttle,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 113-124.

127 Robert Ried, 'Orbiter Entry Aerothermodynamics,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2*** pp 1051-1061.

Figure 7:4.



Source: Robert Ried, 'Orbiter Entry Aerothermodynamics,' Norman Chaffee, (ed) *Space Shuttle Technical Conference: Part 2.*

Along with the development of theoretical models an array of instrumentation was required to recreate boundary-layer transition from laminar to turbulent flows in the laboratory. The foundation for the definition of the reentry aerothermodynamics environments were the wind tunnel test data taken from scaled models of the orbiter.[128] Wind tunnels, although a valuable tool, had their limits. The most pressing problem was the scaling-up of data without the introduction of some error or distortion. Although a range of techniques were available, such as pressurizing or cooling the air in the tunnel, chilling the models to cryogenic temperatures, or using helium instead of air, complex mathematical equations were also a necessary part of the prediction process.[129] Complementing wind tunnel activity, therefore, was an increase in the use of computer technology in computational fluid dynamics. Many of the engineers and managers at Ames were eager to enter what was then a new research field as Dean Chapman, Chief of Ames's Thermo- and Gas-Dynamics Division recalled:

> I'd been out of fluid mechanics for eight or nine years when I took over the division in 1969. When I reviewed the field and saw what computers were doing even then, it became clear to me that they could do a lot of things that I as an

128 ***Ibid.***

129 Paul Ceruzzi, ***Beyond the Limits: Flight Enters the Computer Age*** (Cambridge, Massachusetts, MIT Press, 1989), chapter 7.

experimentalist never dreamed about, so I decided to press into that area.[130]

In 1970 the Theoretical Branch and the Hypersonic Free-Flight Branch were combined to form the new Computational Fluid Dynamics Branch. Ames, however, had the poorest computer facilities within NASA and both Ames Director, Hans Mark and Chapman sought to remedy this situation quickly. The collapse of the Air Force's Manned Orbital Laboratory Program left available an IBM 360-67, which was immediately aquisitioned by Ames in a most unusual manner. Hans Mark had Ames people in Sunnyvale on the very day that the Manned Orbital Laboratory closed down, pulling the computer out before it was declared surplus and installing it at Ames. The acquisition of the IBM 360-67 opened the door for an aggressive research programme by the Computational Fluid Dynamics Branch. Soon after, Ames acquired the Illiac IV (a supercomputer capable of performing 300 million calculations per second and storing one trillion bits of information at a time) through more usual channels. Mark and Chapman both saw the acquisition of Illiac as the deciding factor in establishing Ames as *the* NASA Center for computational fluid dynamics.[131] Its performance was so revolutionary

130 Dean Chapman, quoted in Elizabeth Muenger, ***Searching the Horizon: A History of Ames Research Center*** (Washington DC, NASA, Scientific and Technical Information Branch, 1985), p 173.

131 Hans Mark, Arnold Levine, ***The Management of Research Institutions: A Look at Government Laboratories*** (Washington DC, NASA, Scientific and Technical Information Division, 1984), p 81; Elizabeth Muenger, ***Searching the Horizon: A History of Ames Research Center*** (Washington DC, NASA, Scientific and Technical Information Branch, 1985), pp 173-176; Paul Ceruzzi, ***Beyond the Limits: Flight Enters the Computer Age*** (Cambridge, Massachusetts, MIT Press, 1989), chapter 7.

that Mark, Chapman and Melvin Pirtle, head of the Illiac programme, argued that the relationship between wind tunnel testing and computational fluid dynamics was shifting in favour of the latter.[132]

Nonetheless, wind tunnel experiments and computational fluid dynamics worked in parallel to evaluate the reentry environment and aid the design and fabrication of the thermal protection system. For example, computational fluid dynamics showed unusually high temperature regions along the fuselage and vertical tail, caused by vortex flows created by air flow strakes; and wind tunnel experiments revealed that the nose wheel doors and the external tank attachment fittings created premature boundary-layer transition to turbulent flow with a consequential increase in temperature. Such identifications of the environment and effects of design features, contributed to the thermal protection system design and distribution. Combined with the arc-jet tests, which indicated that the ceramic tiles could withstand temperatures of 3 100 degrees fahrenheit, confidence in the system grew.[133]

The amount of data being generated by both computational analysis and wind tunnel experiments was colossal. Indeed, there was so much information that by

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132 Dean Chapman, Hans Mark, Melvin Pirtle, 'Computers vs Wind Tunnels for Aerodynamic Flow Simulations,' ***Astronautics and Aeronautics*** (April 1975), pp 22-35.

133 Memorandum from Charles Donlan to the Associate Administrator for Space Flight, March 25, 1976 (NASA History Office Archive, Washington DC).

early 1976 rumours had begun to circulate around NASA that sufficient caution and care was not being exercised in the review of the data. Concern soon arose within the Office of Manned Space Flight over what steps were being taken by both Ames and Rockwell International, to critically examine the data for errors.[134] A visit to Rockwell International at Downey, California and to Ames, was thus made by members of the Office of Manned Space Flight to discuss the issue. After three days of discussion and review, confidence was raised that the aerodynamic and aerothermal data was being 'carefully and thoroughly assessed.'[135]

Fabrication, Application and Modification: Thermal Protection.

While the process of prediction and wind tunnel testing in the area of reentry aerothermodynamics proceeded, production of the orbiter's thermal protection system got under-way. The transition from laboratory production of the silica thermal protection system to full production had many scale-up problems.

Control of the purity and consistency of the silica fibres presented NASA and Lockheed with their first major production problem. The silica fibre, a key ingredient in the production of the tile, came in an amorphorous form.

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134 Memorandum from Charles Donlan to the Associate Administrator for Space Flight, February 19, 1976 (NASA History Office Archive, Washington DC).

135 Memorandum from Charles Donlan to the Associate Administrator for Space Flight, March 25, 1976 (NASA History Office Archive, Washington DC).

Crystalline forms of the fibre, however, were found to have a thermal expansion coefficient 30 times greater than the amorphorous form. A crucial element of the production process, therefore, was the transformation of the silica fibre from its amorphorous form to a crystalline structure, but this was not an easy procedure. Shrinkage and distortion of the sintered silica composites impeded the formation of crystalline structures that would be acceptable to NASA. To achieve the dimensional stability dictated by shuttle requirements, a silica fibre greater than 99.6 per cent pure was necessary.[136]

Locating fibres with sufficient purity, thus, became a major concern of tile production. Lockheed's supplier, Johns-Manville, were unable to meet all the purity requirements and an alternate source was sought. However, silica fibres provided by other suppliers were much larger in diameter than those provided by Johns-Mansville, which was unacceptable to NASA. The exact diameter of the fibre was considered to be of crucial importance to the tile's thermal performance. NASA, therefore, decided to intervene in Johns-Mansville's production process and introduced extensive post-treatment and rigid process controls, from the selection of the sand used in making the fibre through to the fiberizing and cleaning process, to minimize

136 Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference*** pp 1062-1081.

contamination of the "sub-standard" fibres and bring the Johns-Manville fibres up to an acceptable standard.[137]

Another materials problem was encountered during the production phase of the thermal protection tile early in 1975. In the original design concept, the thermal tile was applied with multiple layers of borosilicate glass coatings to prevent moisture absorption, provide protection against handling damage and provide optical property control (solar absorption). During manufacture and during thermal testing, it was discovered that the multi-layer glass coatings had a tendency to crack or foam. Arc-jet tests at Aimes revealed coating failures on approximately 40 per cent of the tiles when they were exposed to a succession of simulated reentry environments. Possible causes of the coating failures included: problems with glass coating composition, processing cycle errors, glazing cycle errors or problems with coating distribution, but budget restrictions in 1975 deferred any detailed investigation until well into 1976. Finding a solution to the coating problem thus had to wait a further year. Eventually Ames's proposal, to use only a single-layer glass coating, received funding for qualification testing in mid-1976. After a lengthy verification programme, NASA found that the single-layer coating did not foam during production and

137 ***Ibid.***; Lockheed Missiles and Space Co., Inc., Space Systems Division, 'Summary of High Temperature Reusable Surface Insulation Program,' ***Space Shuttle 1976 Status Report for the Committee on Science and Technology US House of Representatives*** (Washington DC, US Government Printing Office, October 1975), pp 325-329.

actually provided a better match with the thermal coefficient of the silica insulation material. The superior performance of the single-layer coating over the multi-layer coating, in many of the tests, ultimately persuaded NASA officials to change the design.[138]

Once these two key materials problems had been solved, full-scale production could begin. Technical matters, however, were not the only obstruction to tile production. Funding limitations in 1975 resulted in a substantial modification to the shuttle programme's schedule. In the development of the thermal protection system, the primary impact of the budget restrictions was to defer the procurement of special tooling equipment. This delayed the completion of the production facility in Sunnyvale, California;[139] as Johnson's Director, Christopher Kraft recalled:

> We made a decision to put off building the tile factory, because we didn't have the money. We had to put the money into the schedule and we had to develop the schedule ... and we just decided we could wait a couple of years.[140]

The Sunnyvale plant contained some of the most modern manufacturing equipment then available, including:

138 W.H. Morita (ed) ***Space Shuttle System Summary*** p 110; Lockheed Missiles and Space Co., Inc., Space Systems Division, 'Summary of High Temperature Reusable Surface Insulation Program,' ***Space Shuttle 1976 Status Report for the Committee on Science and Technology US House of Representatives*** (Washington DC, US Government Printing Office, October 1975), pp 325-329; Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference*** pp 1062-1081.

139 Lockheed Missiles and Space Co., Inc., Space Systems Division, 'Summary of High Temperature Reusable Surface Insulation Program,' ***Space Shuttle 1976 Status Report for the Committee on Science and Technology US House of Representatives*** (Washington DC, US Government Printing Office, October 1975), pp 325-329.

140 Christopher Kraft, interview with the author, September 1, 1995.

precision controlled kilns and furnaces, numerically controlled milling machines and the most up-to-date blending and slurry casting equipment. As with flow dynamics analysis, computers played an important role in the fabrication of the thermal protection system. Orbiter configuration coordinates were plotted from a Rockwell engineering data base, and then converted into computer programmes. These programmes then drove the numerically controlled mills that machined the tiles into precise dimensions.[141]

By the end of 1978, application of the complex array of thermal protection tiles to the shuttle orbiter, Columbia, was nearing completion. It was a complex process. Many of the 33 000 tiles had been formed into individually specific shapes, determined by the aerodynamic and aerothermodynamics data that governed the computer-controlled milling machines. Thus, every tile was stamped with a number, which correspond to a precise position on the orbiter. Each tile then had to be applied individually, checked for any differences in height that might induce turbulent flows, and carefully indexed before being "glued" to the structure. In addition, a gap of no less 0.010 inch had to be ensured between each tile to allow for thermal expansion and contraction: and for the flexing of the orbiter's wing surface during flight. The application rate

141 Robert Dotts, Donald Curry, Donald Tillian, 'Orbiter Thermal Protection System,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference*** pp 1062-1081.

was slow and was further hindered by fragility of the tile material. On average, one technician applied one tile per week.[142]

As the planned September 1979 launch date approached, Rockwell found themselves behind schedule with the tile application. To avoid adverse publicity, NASA decided that the remainder of the tiles could be attached at Kennedy. So on March 24, 1979, Columbia was airlifted atop NASA's Boeing 747 to the launch Center with around 6 000 tiles left to install.[143] The plan did not, however, go as intended. A sizeable amount of the tiles were lost during the flight from California to Kennedy. As a public relations exercise it was a disaster. It appeared to the media that if the most advanced spaceship in the world could not even fly from California to Florida without tiles falling off, then how was it suppose make the journey into space?[144] Most of the tiles that were lost were "dummies", put in place as substitutes due to some concern about the effects of turbulence on the "actual" tiles, but the event severely damaged NASA's reputation.

Towards the end of 1979, however, NASA found that it had a much larger problem. Due to budget and schedule

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142 'Thermal Tiles Applied to Orbiter 102,' ***Aviation Week and Space Technology*** (November 27, 1978), p 64; 'F-15 Used in Shuttle Tile Test,' ***Aviation Week and Space Technology*** (February 25, 1980), p 23; Gregg Easterbrook, 'The Spruce Goose of Outer Space,' ***The Washington Monthly*** 12, (1980), pp 32-48.

143 Bruce Smith, 'Loss of Tiles Delays Orbiter Ferry Flight,' ***Aviation Week and Space Technology*** (March 19, 1979), pp 21-22.

144 Transcript from NBC 6:30 pm News, NBC TV, December 21, 1979 (NASA History Office Archive, Washinbton DC).

pressures, NASA had decided to move ahead with the tile fabrication and installation before the final aerodynamic loads and stress analysis had been completed. The design of the tiles was, therefore, based on the initial predictions that had emerged from these studies. As the predictions had become more refined they highlighted a serious weakness in the strength of the tiles.[145] As Space Shuttle Manager, Robert Thompson, recalled:

> One of the things that we got into a little bit of difficulty with, we didn't characterize the tile materials as thoroughly as we should have.[146]

And Johnson's Director Christopher Kraft remembered:

> When we finally got the factory built and started producing the tiles, we got enough tiles to run a sufficient statistical sample, and low and behold the strength was only half what we thought it was.[147]

Late in 1979, NASA suspected that between 10 000 to 12 000 tiles were below the "new" specifications. But, as the programme turned in 1980, aerodynamic and aerothermodynamics data were predicting that up to 31 000 tiles would need to retested.[148]

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145 Robert Thompson, ***Von Karman Lecture*** pp 11-12.

146 Robert Thompson, interview with the author,

147 Christopher Kraft, interview with the author, September 1, 1995.

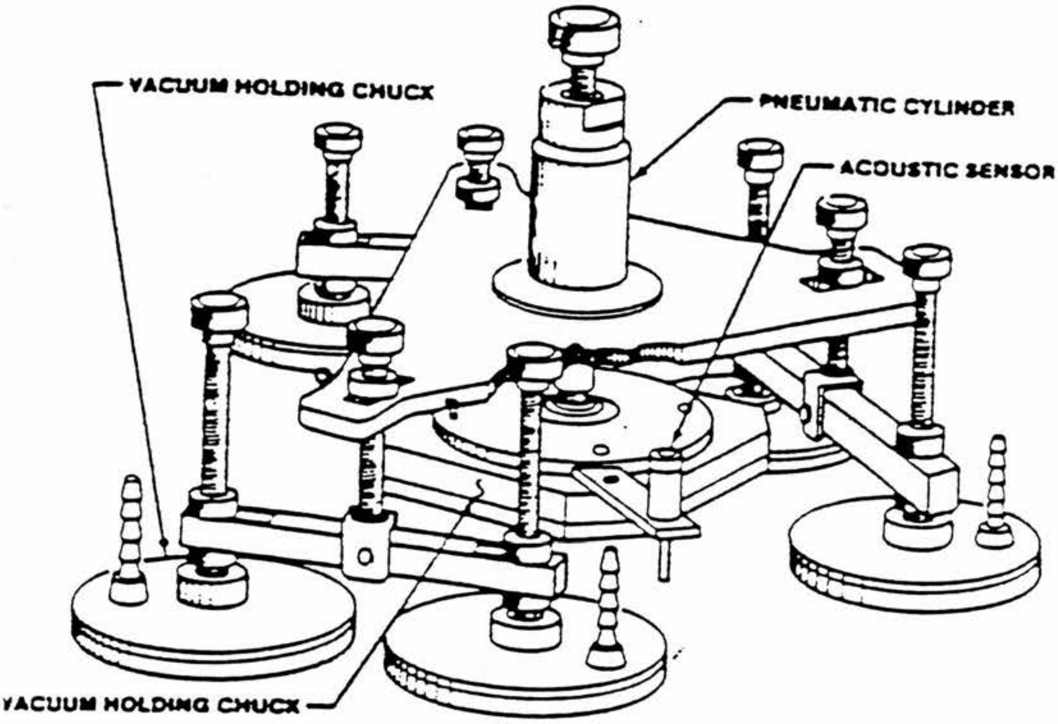
148 'NASA, Contractor Push New Tile Tests,' ***Aviation Week and Space Technology*** (October 15, 1979), p 44; Craig Covault, 'Kennedy Center Starts Shuttle Stacking,' ***Aviation Week and Space Technology*** (November 5, 1979), pp 18-19; Craig Covault, 'Shuttle Project Faces New Problems,' ***Aviation Week and Space Technology*** (December 10, 1979), pp 20-21; 'Orbiter Protective Tiles Assume Structural Role,' ***Aviation Week and Space Technology*** (February 25, 1980), pp 22-24.

The first problem NASA had, was how to test the tiles while they were still on the orbiter. What NASA came up with was a "proof-test device" that combined a vacuum chuck, which attached to a single tile, a pneumatic cylinder, which applied the specified load, and six pads, which would be attached to the surrounding tiles to react to the load (see figure 7:5). The device would then stick to the orbiter, rather like a plunger, and attempt to pull a single tile off, within a specified load. If the tile stayed fixed, then it passed the test. If it came off, then clearly it didn't. Although a simple and effective solution, a second problem emerged: what if the test itself weakened the tile? To solve this problem Kennedy's engineers attached an acoustic sensor to the proof-test device to monitor the acoustic emissions from fibre breakage. This involved the establishment of a large scale laboratory programme to arrive at a failure criteria. The programme simulated the flight loads over 100 missions and monitored the changing acoustic signatures as the tiles failed.[149]

The next problem for NASA was what to do with the tiles that came off. Initially, the "repair" concept was to install a graphite sheet under the tiles to increase their adhesion to the orbiter. However, this was abandoned quite

149 William Schneider, Glenn Miller, 'The Challenging "Scales of the Bird": Shuttle Tile Structural Integrity,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** pp 403-413.

Figure 7:5.



PROOF TESTING DEVICE.

Source: William Schneider, Glenn Miller, 'The Challenging "Scales of the Bird": Shuttle Tile Integrity,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2.***

early for a simpler process known as "tile densification", which involved coating the surface facing the orbiter with a colloidal silica coat. This provided the tiles with a new surface that spread the loads more evenly. However, having been forced into a major modification of its tile application programme, NASA adopted the change with caution.[150] Many at NASA believed that the tile problems should never have occurred and laid the blame on Rockwell. George Jeffs, President of Rockwell International Aerospace Operations, told *Aviation Week and Space Technology*:

> I think its a fair criticism that we didn't define the problems more clearly. ... We worked too hard on the quality of the material alone and waited too long for the thermal analysis while awaiting a detailed structural definition. Perhaps it was a bit too long to understand what the [orbiter structural deflections] might be and their effects in the tiles. I am troubled that we are suffering a lot of shots at our engineering reputation because of the bloody tiles, and we are doing everything we can to clean them up.[151]

Kennedy's engineers hoped that the data obtained from the "pull-tests" would enable a relaxation of requirements thus reducing the reapplication number. But, by the end of 1979, Kennedy had pulled off and reapplied over 12 000 tiles. Originally the densification process was restricted to the black tiles along the bottom of the orbiter, however, early in 1980 there was growing concern about

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150 *Ibid;* Craig Covault, 'Kennedy Center Starts Shuttle Stacking,' ***Aviation Week and Space Technology*** (November 5, 1979), pp 18-19.

151 George Jeffs, quoted in, 'Orbiter Protective Tiles Assume Structural Role,' ***Aviation Week and Space Technology*** (February 25, 1980), p 22.

As the programme moved through 1980, it became apparent that the tile problem was a lot more serious than had been anticipated; and concern soon focused on the "special tiles" around the wing leading edge, the windshield, the undercarriage doors, the tail, and tiles in other areas that did not have square or rectangular shapes. These special tiles were often located in areas that would endure very complex air flows that could not be easily analyzed and they were not amenable to the pull-test technique. Thus, NASA had to go back to wind tunnel testing on the tiles. However, this was both expensive and time consuming, so NASA decided to select only certain locations from several of the most complex air flow fields to build up a data set (see figure 7:6). To reinforce the analysis, the scale model tests in the wind tunnel were correlated with similar air flows on fighter aircraft. NASA attached some of the tiles to wing sections on an F-15 and an F-104 and then flew the aircraft through flight conditions up to 1.4 times the severity of those expected on the shuttle.[154]

The test programme was not completed until January 1981. NASA's revised first launch date had been set for March 1981, however, the tests showed up serious flaws in the special tiles. It was speculated from the data, that the high pressures of ascent could lift the windshield

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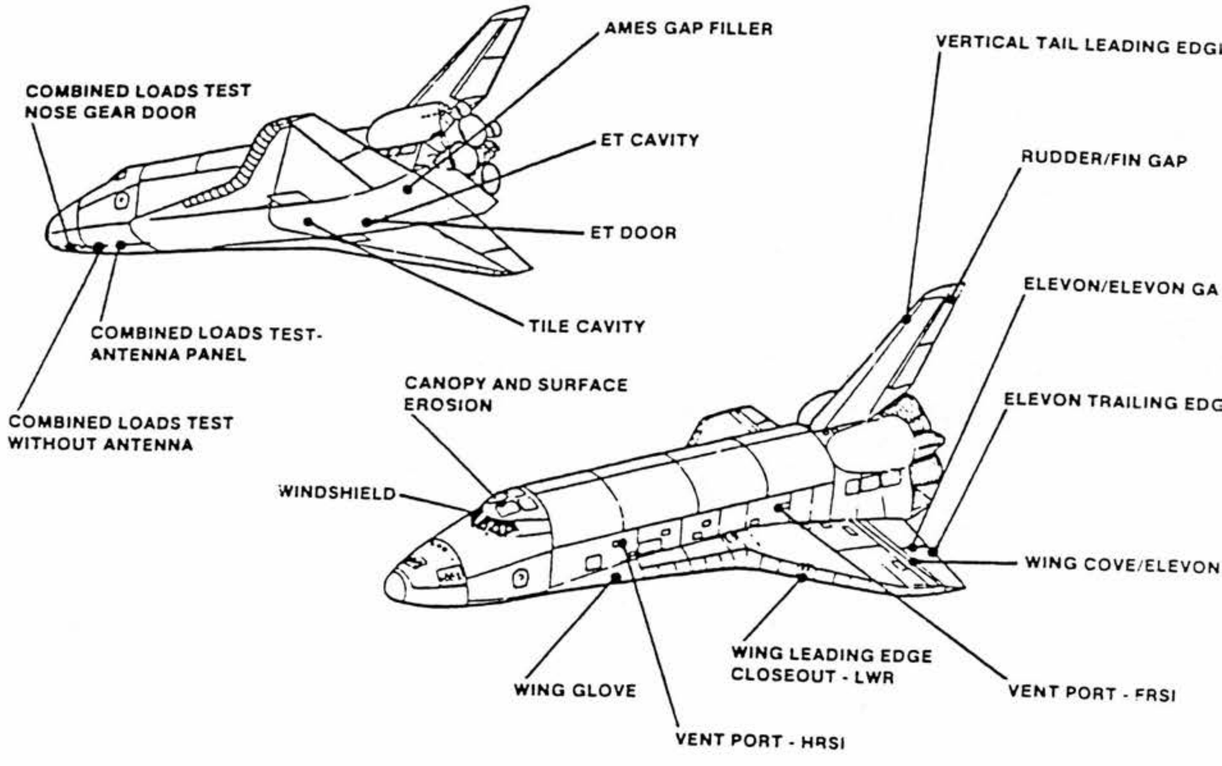
154 'F-15 Used in Shuttle Tile Test,' ***Aviation Week and Space Technology*** (February 25, 1980), p 23; 'Space Shuttle Tile Tests Completed,' ***Aviation Week and Space Technology*** (January 19, 1981), p 30.

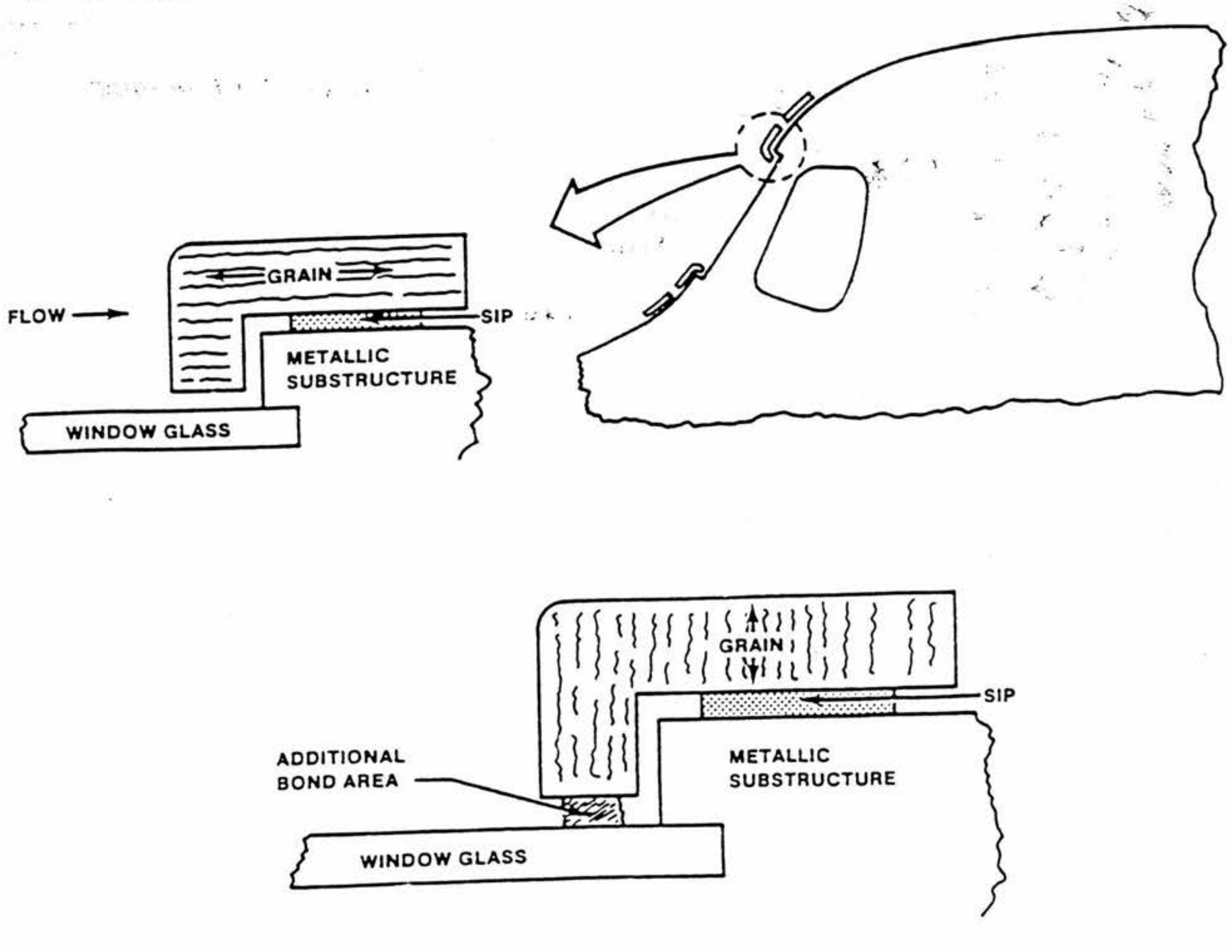


TPS FLOW PROGRAM TEST ARTICLE LOCATIONS.

Figure 7:6.

Source: William Schneider, Glenn Miller, 'The Challenging "Scales of the Bird": Shuttle Tile Integrity,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2.***

Figure 7:7.



WINDSHIELD TILES.

tiles from their moorings. As with all the tiles, the windshield tiles had been machined from a block of ceramic in such away as to ensure that all the fibres run in parallel to the shuttle's surface. This was done, because analysis had demonstrated that a parallel grain orientation would minimize the heat transfer to the orbiter's aluminum skin. However, this grain orientation caused a reduction in the tiles strength because of the relatively low number of vertical fibres. The first solution, therefore, was to machine new tiles with the fibres running perpendicular to the orbiter's surface. This would provide the strength, but it would also reduce thermal efficiency. Thus, a second solution, combined with the first was also necessary. On further analysis it was found that the window itself would act as a heat sink, so NASA decided that by bonding the part of the tile that overhung the window directly to the glass this would increase the thermal capacity of the tile (see figure 7:7).[155]

The testing also determined that the corner tiles on the wing trailing edge and flaps would fail within seconds of engine and booster ignition. To solve this problem NASA went back to an older idea that had long been abandoned: a mechanical attachment called the auguer (see figure 7:8). The auger system was twisted into the tile and then

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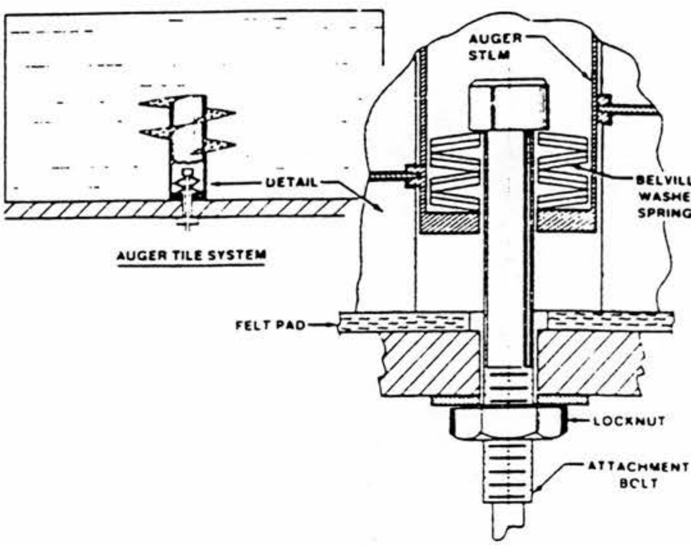
155 William Schneider, Glenn Miller, 'The Challenging "Scales of the Bird": Shuttle Tile Structural Integrity,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference, Part 1*** pp 403-413.

Figure 7:8.



AUGER T._E ATTACHMENT.

Source: William Schneider, Glenn Miller, 'The Challenging "Scales of the Bird": Shuttle Tile Integrity,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 2.***

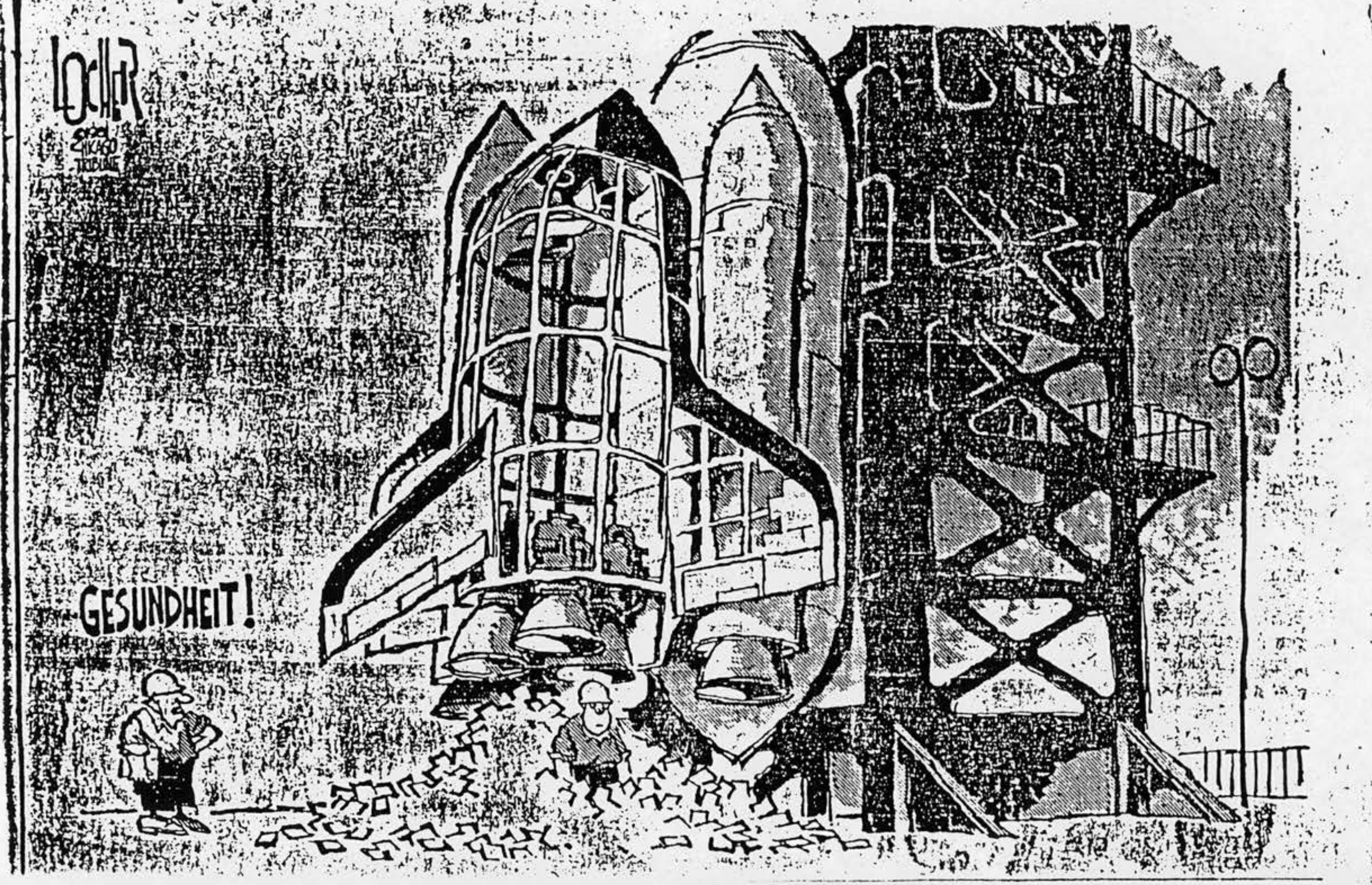
attached to the substructure via bolts. The key component was a Belville washer, which acted as a soft spring to prevent the loads from the bolts breaking the fragile tile.[156]

After two years of testing and redesign, NASA's confidence in the thermal protection tiles was reinforced and by March 1981, many of the problems were deemed solved. However, this confidence was not shared outside of NASA and, as Columbia prepared for its first flight in April 1981, the question of the tile's performance was still a matter of doubt.[157]

156 *Ibid.*

157 Christopher Kraft, interview with the author, September 1, 1995.

Oct. 16, 1981



Chapter 8

A Crisis of Confidence

> It is clear that the true problems of our nation are much deeper - deeper than gasoline lines or energy shortages, deeper even than inflation or recession ... The threat is nearly invisible ... it is a crisis of confidence. ... Confidence has defined our course and has served as a link between generations. We have always believed in something called progress. ... We ourselves are the same Americans who just ten years ago put a man on the Moon. And we are the generation that will win the war with the energy problem, and in the process rebuild the unity and confidence of America.[1]

In the spring of 1979 a second oil shock struck at the heart of the US economy. Petrol lines, which had not been seen since 1973, reappeared, but this time they were accompanied by panic, hoarding and even violence. After a ten day summit at Camp David, where President Jimmy Carter took advice from leading politicians and experts, the President returned to Washington DC to deliver a long awaited speech on the energy crisis. In part, the speech was a declaration in the faith of the technical capabilities of the nation to solve any problem, or any obstacle that lay in its path. The Lunar landing was upheld as a symbol of progress, a sign of confidence and world

1 President Jimmy Carter, 'Crisis of Confidence Address, July 15, 1979,' reprinted in Richard Hofstadter, Beatrice Hofstadter, (ed) ***Great Issues in American History: From Reconstruction to the Present Day, 1864-1981*** (New York, Vintage Books, 1982), pp 522-524.

leadership. Yet, those same people that had placed an American on the Moon were experiencing their very own crisis of confidence.

Electorial Passage.

Carter's victory in the 1976 Presidential election came at a time when the US was still suffering from the "humiliation" of Watergate and Vietnam. Carter's apparent youth, confidence and integrity, attracted wide popular support. President Ford, by contrast, appeared uninspiring and uncertain, offering only a second-rate leadership over a country that was threatening to turn into a second-rate power. Unlike Ford, Carter promised optimism and a vision for the future. He had also developed a political style, which exhibited a great concern for the people and an antipathy toward the power exerted by pressure groups and big business. During his acceptance speech as the Democratic candidate, on July 14, 1976, Carter spoke of the need for a national health system, cuts in defense spending and policies designed to help the poor and boost employment.[2]

President Ford, meanwhile, had submitted a defense budget to Congress, which called for a significant increase in military hardware procurement. In part, the policy stemmed from a perceived decline in the US defense posture

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2 Ian Derbyshire, ***Politics in the United States: From Carter to Bush*** (Edinburgh, W & R Chambers Ltd, 1988), pp 24-29.

brought about by detente with the Soviet Union and the Strategic Arms Limitation Talks (SALT) agreements of 1972.[3] During his presidential campaign Carter criticized this policy. Carter's views on national security stemmed from an approach to foreign policy and defense that questioned the vast resources committed to defending US interests. His response was blunt: the US public would no longer tolerate the siphoning off of more tax dollars into Pentagon coffers. Such a policy stance, he argued, would halt economic recovery and only further weaken an already faltering economy. Towards the end of 1976, it appeared to the US public that Carter was right, as the economic indicators pointed to a slow down in the economy. However, the slow down was only temporary and recovered before Carter had a chance to implement his expansionist policies. Nevertheless, the Carter Administration was fortunate in the sense that the economy appeared bad enough for the majority to believe that it was his policies and not Ford's, that were required.[4]

To NASA, Carter was an enigma, at least as far as the shuttle programme was concerned. He was an engineer by training, but many at NASA did not think of him as a space

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3 Robert Hotz, 'Ford's Cadillac Budget,' Editorial, ***Aviation Week and Space Technology*** (January 26, 1976), p 11.

4 David Callahan, ***Dangerous Capabilities: Paul Nitze and the Cold War*** (New York, Harper Collins, 1990), pp 398-399; Stephen Woolcock, 'The Economic Policies of the Carter Administration,' M. Glenn Abernathy, Dilys M. Hill, Phil Williams, (ed) ***The Carter Years: The President and Policy Making*** (London, Frances Pinter, 1984), pp 35-36.

programme supporter.[5] Despite pre-election statements supporting both the agency and the shuttle, NASA officials had remained cautious about how they expected the agency to fare under the Carter Administration.[6]

The key issue for NASA under the new Administration was orbiter procurement. Funding for Orbiters four and five, argued NASA officials, would have to begin in the FY 1978 budget cycle if the agency was to maintain the wide range of shuttle launches planned for the 1980s.[7] However, attempts by NASA to secure a five orbiter fleet and the debate surrounding the undertaking, had actually begun long before Carter stood for election. In 1976, the debate intensified because NASA was uncertain about the political terrain. Many at the agency were concerned that if approval on fleet size was not forthcoming before the election, then NASA would have to go through a completely new justification procedure for the shuttle; and there was a real sense of trepidation about the outcome.[8]

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5 Christopher Kraft, interview with the author, September 1, 1995; John Yardley, interview with the author, August 9, 1995; Bill Sneed, interview with the author, August 21, 1995; Hans Mark, interview with the author, September 8, 1995.

6 E. Kozicharow, 'Shuttle Support Seems Assured,' ***Aviation Week and Space Technology*** (November 8, 1976), pp 14-15; 'Space Agency Readies Carter's Briefing,' ***Aviation Week and Space Technology*** (November 15, 1976), p 22.

7 'Space Agency Readies Carter's Briefing,' ***Aviation Week and Space Technology*** (November 15, 1976), p 22.

8 Memorandum from James Fletcher to John Yardley, March 28, 1977 (NASA History Office Archive, Washington DC).

Questions Over the Size of the Space Fleet.

In 1971, when NASA was still pushing its plan for a fully-reusable two-stage shuttle, the Office of Manned Space Flight pictured a fleet complement of five orbiters and four boosters, which would operate out of two launch sites.[9] In 1973, when the issue was reexamined in the light of major modifications to the shuttle's configuration, NASA and the Air Force preserved both the size of fleet complement and the launch site strategy.[10] Five orbiters, argued NASA, would be 'sufficient to support the 1971 traffic model of 581 shuttle flights.'[11] Indeed, five orbiters were judged able to support 581 flights with a substantial margin for growth.[12] And with three orbiters allocated to Kennedy and two at Vandenburg, future civilian and military space hardware would be transported and serviced by the same technological system.[13]

The grandiose plans formulated at Office of Manned Space Flight envisaged a space shuttle service that would administer all future space activity. The image conveyed a

9 Merrit Preston, Memorandum, June 4, 1971 (Kennedy Space Center Archive, Florida).

10 ***NASA/DOD Space Shuttle Orbiter Fleet Size Analysis***, prepared by the Office of Manned Space Flight and US Air Force Systems Command, May 15, 1973 (NASA History Office Archive, Washington DC).

11 ***Ibid.*** pp 8-9.

12 Estimates of it potential in 1973 went as high as 834 flights over the same twelve year period. M. Malkin, Memorandum to Associate Administrator for Manned Space Flight, May 30, 1973 (NASA History Office Archive, Washington DC).

13 ***NASA/DOD Space Shuttle Orbiter Fleet Size Analysis***, prepared by the Office of Manned Space Flight and US Air Force Systems Command, May 15, 1973 (NASA History Office Archive, Washington DC).

future of clean, reusable and routine space travel, where all other launch vehicles had been displaced in favour of the shuttle.[14] A shuttle monopoly was central to the vision of economic space travel. Monopolization was a necessary objective and the benefits associated with economies of scale served as its rhetorical confirmation. Paralleling the economic discourse, therefore, was a debate over the size of a shuttle fleet; the larger the fleet, the greater the rewards. Behind the rhetoric though, lay a simple strategy. If NASA could persuade those in the political arena on the benefits of economies of scale, then its production budget would be vastly increased. As the programme advanced however, events conspired to frustrate the aspirations of NASA's planners.

NASA had an authorized development budget which provided funding for the first two orbiters and a production budget that included funding for a third. Beyond that, there was no budget planning for a fourth or fifth orbiter.[15] The additional orbiters were excluded from NASA's budget projections because during the campaign to gain political approval, both the White House and the Congress had perceived orbiters four and five as an Air

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14 For an example see, James Fletcher, 'NASA's Aerospace Programs: Options for the Future' ***Strategic Review*** Vol 2, No.2 (Spring, 1974).

15 George Low, Malcolm Currie, Memorandum to the Secretary of Defense and the NASA Administrator, 8 May, 1976 (NASA History Office Archive, Washington DC).

Force procurement responsibility.[16] During the early planning phases the idea of a NASA/DOD partnership had been embraced by both agencies. A perception that each partner would share the funding of building the orbiter fleet, thus persisted into the mid-1970s. By 1975 however, it had become clear to NASA that the DOD had shifted its position.[17]

> There was some talk about the Air Force buying some orbiters, where they would become what we called blue shuttle's; Air Force blue shuttles. That just became too expensive at the time, so our ... plans in the Air Force was to use the NASA fleet.[18]

The Congress had also become aware of a change in the DOD/NASA relationship in early 1975 when a General Accounting Office report indicated that the Air Force had not been directed by the DOD to included any funding for shuttle purchases in their budget submissions.[19] The DOD's view of its role had thus evolved from partner to major user. As Lieutenant General, Forrest McCartney reflected, many sections of Air Force were showing increased scepticism in NASA's proclamations about the shuttle; and were especially concerned about NASA's drive towards a policy of monopolization:

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16 Memorandum from NASA Comptroller to Associate Administrator for Space Flight, April 21, 1976 (NASA History Office Archive, Washington DC).

17 NASA, Draft Issue Paper on Orbiter Procurement, May 8, 1976 (NASA History Office Archive, Washington DC).

18 Forrest McCartney, interview with the author, July 28, 1995.

19 GAO, ***Staff Study: Space Transportation System***, February 1975 (General Accounting Office Distribution Center, Washington DC), pp 51-52.

> We in the Air Force felt that NASA had overstated the capability and need for the shuttle. ... So I think, in those days the Air Force could see in the early seventies [that the shuttle] would become the only launch vehicle that the country [would have]. The Air Force always had reservations about that, always opposed that and always felt that they did not want to be confined or dedicated to one vehicle.[20]

As the programme turned into 1976, confrontation arose between NASA and the DOD over which agency was to ask Congress for funding to purchase the two additional orbiters.[21] In testimony before the Senate Space Committee the Pentagon stated that paying for the additional orbiters would exceed the figure that it calculated would be cost effective for taking part in the shuttle programme.[22] Confirmation of the DOD's intentions came during an informal meeting between NASA Associate Administrator, George Low, Associate Administrator for Space Flight, John Yardley, the Pentagon's director of research and engineering, Malcolm Currie and other members of the DOD in May 1976. Currie indicated at that meeting that he personally would support a five orbiter fleet, but he warned NASA that if the DOD was directed to absorb the funding for the additional orbiters, then 'its support for

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20 Forrest McCartney, interview with the author, July 28, 1995.

21 Victor McElheny, 'Aerospace Contracts, Put at $1 Billion, Hinge on Debate Over Space Shuttles' ***The New York Times*** (August 24, 1976), p 37.

22 ***Ibid.***

the shuttle would vanish.'[23] Indeed, Malcome Currie had supported a five orbiter fleet when he told the Congress earlier that year that the three orbiters planned by NASA would not be adequate for DOD needs.[24] Nevertheless, it was clear to NASA that orbiters four and five would not be manufactured in the near future without a significant increase in the agency's budget.

> I do not currently see the agency with the capability to undertake the funding of these orbiters based on budget priorities and within the likely budget allowances during the applicable period.[25]

George Low, forced by the DOD's new position, thus set in motion a campaign to convince Congress during 1976 that NASA should fund orbiters four and five.

> I believe that ... providing over-allowance funds to DOD for Orbiters 4 and 5 should ... be ... discarded. The reason for doing this is that there are people in the Senate who feel strongly that DOD should carry its share of Shuttle development and procurement, and, therefore, should buy those two orbiters. What you have to demonstrate ... is that it is all the same taxpayer's money and that it therefore really dosen't matter whose budget it is in ... and that putting it in the NASA budget greatly simplifies other matters.[26]

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23 George Low, memorandum for the record, meeting with Malcolm Currie on orbiter procurement and reimbersment policy, May 19, 1976 (NASA History Office Archive, Washington DC).

24 'Pentagon Says Three Shuttle Orbiters Inadequate' ***Defense/Space Business Daily*** (March 4, 1976), pp 25-26.

25 Memorandum from NASA Comptroller to Associate Administrator for Space Flight, April 21, 1976 (NASA History Office Archive, Washington DC).

26 George Low, Memorandum to Associate Administrator for Space Flight, April 19, 1976 (NASA History Office Archive, Washington DC).

Argumentation in favour of a five orbiter fleet complement was, nonetheless, constructed on weak foundations. Indeed, George Low had to condemn an internal NASA position paper, which indicated that a three orbiter fleet combined with a fleet of expendable launch vehicles would prove just as economical.[27]

> If this is the best we can do, we might as well give up now. There is no way that we will get funding over and above the NASA budget for Orbiters 4 and 5 unless we can prepare a much more logical and factual document. The argument [presented] ... leads me to the conclusion that we should buy only 3 orbiters and maintain a Titan III capability. By your own figures, we could maintain this capability for five to ten years at a cost considerably less than the cost of the additional two orbiters.[28]

George Low and Malcolm Currie thus recommended that NASA and the DOD assumed a political position, which claimed the need for six orbiters; all to be built by NASA.[29] To camouflage fractures in the argumentation the five orbiter fleet, described as *sufficient* in 1973, was presented in 1976 as the *minimum* fleet size. NASA Administrator, James Fletcher, told the Director of the Office of Management and Budget, James Lynn toward the end of 1976:

> a fleet of five orbiters is the *minimum* fleet size which should be acquired to support the national requirements projected during the 1980-

27 NASA draft issue paper on orbiter procurement, April 7, 1976 (NASA History Office Archive, Washington DC).

28 George Low, Memorandum to Associate Administrator for Space Flight, April 19, 1976 (NASA History Office Archive, Washington DC).

29 A Proposed Memorandum written by George Low and Malcolm Currie to be signed by NASA Administrator, James Fletcher and Secretary of Defense, Donald Rumsford, and sent to the President or the director of the OMB, May 8, 1976 (NASA History Office Archive, Washington DC).

> 1991 period. ... A decision now not to procure the additional orbiters would impose a tight operational ceiling on our future space capability which could adversely impact this nation's leadership in space technology and the attainment of the significant benefits to mankind we are certain will evolve through new an innovative uses of the Space Shuttle fleet. ... Since the initiation of the ... program in 1972, NASA and DOD have funded or developed budget plans for over $11 billion in FY 1978 budget dollars toward development and support of a viable ... Space Transportation System. We believe that it is prudent to add the approximate additional ten percent to this significant investment to practically double our space flight capability and to provide a fleet size we believe is the *minimum* essential to move forward in the exploitation of space.[30]

Nevertheless, NASA failed in its attempt to secure orbiter production funding before the presidential election. Instead the debate on fleet size continued on into the Carter Administration.

Early in 1977 the General Accounting Office presented a report to the Congress on the progress of shuttle development and NASA planning. The report was exceptionally critical on the question of orbiter procurement. Five orbiters, claimed the General Accounting Office, was far in excess of what would be required. Using historical data rather than NASA's space traffic models, the General Accounting Office came to the conclusion that two orbiters would be sufficient to serve space activity in the 1980s. It thus recommended that Congress should defer the

30 Letter from James Fletcher to James Lynn, Director Office of Management and Budget, October 22, 1976 (NASA History Office Archive, Washington DC), my emphasis.

construction of two or three of the planned five orbiters.[31] NASA, concerned that the report would influence Congress to hold back on orbiter production appropriations, defended its position. John Yardley told *Aviation Week and Space Technology*:

> They [the General Accounting Office] haven't grasped the reason for five orbiters. ... [E]ven if we went down to 200 flights in the 12 year period, we still made out cheaper with a five-orbiter fleet compared to a mix of orbiters and expendable launch vehicles.[32]

And James Fletcher, prior to leaving NASA in May 1977, commented:

> It is my considered judgement that the national interest will be best served by committing now to a five orbiter fleet, and that the eventual size of the national space program and the individual budgets of the several user agencies will in no way be predetermined by this decision. A five orbiter fleet provides a cost-effective launch posture even at the levels of space activity of last year.[33]

However, the General Accounting Office pointed out that:

> The extent to which space flight activity will increase is largely dependent on the willingness of the Congress to fund new space projects and applications because approximately 80 percent of the projected payloads will be Government financed.[34]

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31 GAO, ***Space Transportation Systems: Past, Present, Future***, Report to the Congress, May 27, 1977 (General Accounting Office Distribution Center, Washington DC).

32 John Yardley, quoted in, Craig Covault, 'Shuttle Criticism Worries NASA,' ***Aviation Week and Space Technology*** (April 11, 1977), p 12.

33 James Fletcher, quoted in 'Delay Urged on Funds for Two Orbiter's,' ***Aviation Week and Space Technology*** (June 13, 1977), pp 87-89.

34 GAO, ***Space Transportation Systems: Past, Present, Future***, Report to the Congress, May 27, 1977 (General Accounting Office Distribution Center, Washington DC), p 57.

James Fletcher's resignation as NASA Administrator became effective on May 1, 1977. Frank Press, Carter's science advisor, pushed to have Robert Frosch as the fifth NASA Administrator. Frosch, a weapons scientist with a background in physics, was a friend of Press, so thought loyal to the Carter Administration. During his first meeting with the President, Carter asked Frosch to closely examine the shuttle programme to determine if it should be shut down. Thus, Frosch found out very quickly that he was working with an Administration that was trying to free itself from the past. Every programme had to be examined, with the view that if it was not cost-effective it should be eliminated. Frosch eventually decided that the shuttle programme was a valuable asset, because it was the only project that maintained a human space programme.[35]

Meanwhile, the new Office of Management and Budget, under the guidance of Vice President, Walter Mondale, were examining methods of reducing the shuttle fleet to three orbiters.[36] On November 29, 1977 the Office of Management and Budget called a high-level meeting to discuss the shuttle's future. In attendance was the Director of the Office of Management and Budget, James McIntyre, Secretary of Defense, Harold Brown, Deputy Secretary of Defense, Charles Duncan, Secretary of the Air Force, Hans Mark,

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35 Joseph Trento, ***Prescription for Disaster*** pp 147-149.

36 ***Space Shuttle: Office of Management and Budget Production Options*** February 2, 1977 (NASA History Office Archives, Washington DC).

Director of Central Intelligence, Stanford Turner, and the Director of Defense Research and Engineering, William Perry. The Office of Management and Budget presented three options to the meeting. First, to continue with the current plan, a five orbiter fleet operating out of two launch sites; second, to the cut the shuttle programme back to three orbiters operating from Kennedy only, which involved retaining an expendable launch vehicle capability; or third, a compromise position of constructing four orbiters and leaving the question of a second launch site open for future review. The Office of Management and Budget made a strong argument for the second option on the grounds that it would aid the Administration's near-term budget problems. Hans Mark, a former NASA employee, and Harold Brown refused to accept the Office of Management and Budget's proposal so no decision was made.[37]

Nevertheless, the Office of Management and Budget pushed for some sort of a decision in that year and yet another meeting was held on December 16, 1977 to reach a final settlement. At this meeting Harold Brown took a very strong position against the Office of Management and Budget's proposal. He argued that a three orbiter fleet was unacceptable from the standpoint of national security. His argument was based on the fact that NASA's first two orbiters (Columbia and Challenger) would be heavier than

[37] Hans Mark, ***The Space Station*** pp 71-73.

the following vehicles (Discovery and Atlantis), so they would be unable to lift the DOD's heaviest payloads. At least two of the lighter orbiter's would be required, argued Brown, because the DOD would need a backup in case one of them was lost.[38] Brown's arguments eventually swung Carter's decision over to the compromise position and he reduced the shuttle fleet to four orbiters.[39]

NASA Administrator, Robert Frosch told Congress that Carter's decision was an indication that his Administration had misgivings over whether the shuttle would be capable of conducting all the missions forecast; and that he interpreted the deferment of the fifth orbiter as a policy of caution, by allowing additional time to judge whether it would actually be needed. There was a strong cross-party move in the Congress, however, to reverse Carter's decision. Many in of the space committees believed that a four orbiter fleet would limit civilian space programmes and could place the US in a vulnerable position for the strategic use of space in defense, if one orbiter were lost or damaged. Senator Harrison Schmitt (Republican, New Mexico), a former Apollo astronaut, said that he believed the Carter Administration had a 'great misunderstanding' about the importance of technology to the future of the US. Thus, Congress ignored the proposals of both the Office and

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38 *Ibid.*

39 Dick Baumbach, 'KSC Is Pleased With 4 Shuttles' ***Today*** (January 24, 1978), p 8A.

Management and Budget and the General Accounting Office and four Congressional committees added $4 million in FY 1979 funds to preserve the option for a fifth orbiter.[40]

The Flowering of Financial and Management Crisis.

The shoots of financial crisis, as was shown at the end of chapter 5, surfaced soon after Nixon's reelection in 1972. NASA had faced budget constraints through FY's 1973, 1974 and 1975; and inflationary pressures had also caused NASA's purchasing power to erode. In August 1974, the shuttle's Program Manager, Robert Thompson had expressed concern over the programme's financial future.

> Overall, we feel that the funding available for Shuttle Projects for fiscal years 1975 through 1977 is very marginal since there are no funds available for growth or change allowances.[41]

This remained an explicit concern at NASA, as the agency continued to experienced (what it perceived as) a declining budget posture. President Ford's FY 1977 budget submission to Congress of $3.7 billion enacted a $182.6 million cut in NASA budget request, but more significantly to NASA, the

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40 Craig Covault, 'Fifth Orbiter Support Rises in Congress,' ***Aviation Week and Space Technology*** (February 27, 1978), pp 20-21; 'Fifth Orbiter, Stereostat Voted Funding by House Committee,' ***Aviation Week and Space Technology*** (March 6, 1978), pp 13-14; 'Senate Unit, House Vote Fifth Orbiter,' ***Aviation Week and Space Technology*** (May 1, 1978), pp 22-23; 'Senate Unit to Consider Funds for Fifth Orbiter,' ***Aviation Week and Space Technology*** (July 31, 1978), p 21; 'GAO Sticks To Its Guns On Shuttle Fleet Sites,' ***Aerospace Daily*** (August 8, 1978), pp 161-162.

41 Robert Thompson, quoted in, GAO, ***Staff Study: Space Transportation System***, February 1975 (General Accounting Office Distribution Center, Washington DC), p 4.

total figure represented 'a level approximately 25 percent less than that of a $3.4 billion *constant budget*'.[42]

Given the condition of the US economy and the rhetoric of the presidential election, it appeared that NASA would not suffice any better under a Carter Administration. Although unemployment had fallen from its peak of 9 per cent in 1975, it remained close to 8 per cent in 1976; and inflation hovered around 7 per cent for most of that year. The government's budget deficit stood at $66.4 billion in 1976, which was equivalent to 4.1 per cent of GNP (a record at that time for the US) and federal expenditures accounted for 22.6 per cent of GNP. Once in office, the general objectives of the Carter Administration were: to reduced unemployment to 4.5 per cent by 1981; bring inflation down to 5 per cent; balance the federal budget, reduce government expenditures to 21 per cent of GNP and inject $60 billion into the economy in increased spending on social programmes over the four year term.[43] It was not a programme that favoured large technological projects.

By the end of 1977 a myriad of technical problems were having a cumulative effect on the shuttle programme's financial condition.[44] The shuttle had consumed over $1.2

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42 William Lilly, Memorandum to the Associate Administrator for Space Flight, April 21, 1976 (NASA History Office Archives, Washington DC), my emphasis; NASA's total appropriation for FY 1977 was $3 819 090 000. Ihor Gawdiak, Helen Fedor, ***NASA Historical Data Book Volume IV*** Table 4-16, p 138.

43 Stephen Woolcock, 'The Economic Policies of the Carter Administration,' M. Glenn Abernathy, Dilys M. Hill, Phil Williams, (ed) ***The Carter Years: The President and Policy Making*** (London, Frances Pinter, 1984), pp 36-37.

44 See chapter 7 for details on some of the technical problems.

billion during FY 1977, but additional testing, major redesigns of both hardware and software, and the need for the employment of additional labour in the fabrication of Columbia, had drained the programme's reserves and placed pressure on the agency's overall resources.[45] To save the programme and remain on target for a first launch in March 1979, NASA Administrator Robert Frosch proposed a plan to Congress to shift $100 million from the orbiter production budget (monies allocated to begin building the shuttle fleet) to the design, development and test budget.[46] Although, this plan did not go without some criticism in Congress. William Proxmire announced that his Appropriations Subcommittee would hold a hearing in December to examine, what he saw, as a shuttle cost overrun of $100 million.[47]

> For the first time NASA has admitted that there will be an overrun of between four percent and seven percent in the cost of the space shuttle. Even more disturbing are indications that there may be significant delays in implementing the shuttle system and performance degradations that could impair or destroy the shuttle's cost advantages over the use of conventional expendable launch vehicles. ... These proposed changes may be the tip of the iceberg. Further increased costs along with program delays and

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45 Statement of Robert Frosch before the Senate Appropriations Committee, HUD - Independent Agencies Committee, draft version, November 29, 1977 (NASA History Office Archives, Washington DC).

46 *Ibid*; Robert Frosch, Letter to Representative Edward Boland (Democrat, Massachusetts), November 9, 1977 (NASA History Office Archives, Washington DC); Thomas O'Toole, 'NASA Asks $100 Million Shuttle Fund Shift,' ***The Washington Post*** (December 2, 1977), p A2.

47 'Proxmire Sets Hearing On Space Shuttle Cost,' ***Washington Star*** (November 28, 1977), p 3.

> reduced shuttle performance may just be over the horizon.[48]

In this prediction, Proxmire turned out to be correct. In January and February 1979, NASA officials went before Congress to request an additional supplement of $185 million to keep the shuttle programme on schedule for a 1979 launch date, which was approved on the basis of Frosch's testimony that the FY 1980 budget fully supported the development programme.[49] Nevertheless, in this prediction, Frosch was unequivocally wrong.

NASA's first space flight shuttle, Columbia, arrived at Kennedy in late March 1979. With the first launch due some months later, President Carter announced:

> The first great era of space is over. The second is about to begin.[50]

The statement, largely based on the assurances coming from NASA, was, nonetheless, premature. The shipment of Columbia to Kennedy was, as one Johnson Official, Herb Yarbrough, recalled, primarily done for political reasons.

> [When Columbia] went down [to Kennedy] ... it was not ready for delivery, but the program had a

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48 William Proxmire, Press Release from the Office of Senator William Proxmire, November 28, 1977 (National Air and Space Museum Archives, Washington DC).

49 'NASA Budget Provides No Real Growth,' ***Aviation Week and Space Technology*** (January 22, 1979), p 16; 'Frosch Defines FY 1980 Budget,' ***Roundup*** (Houston, Texas, NASA, Johnston Space Center, January 26, 1979) , p 1; 'House Unit Okays $185 million FY '79 Supplement For Shuttle,' ***Defense/Space Daily*** (March 7, 1979), p 34.

50 Jimmy Carter, quoted in ***NASA Activities***, May, 1979 (NASA History Office Archive, Washington DC).

> milestone and we had budget problems and not delivering on time wouldn't have helped that.[51]

March 1979 had been the predicted launch date for a number of years. Thus, getting the shuttle to Kennedy by that date had become a key objective. Yet, it soon became apparent to those at Kennedy that the vehicle was nowhere near ready to fly, as Rockwell engineer (Kennedy Div.), John Tribe, remembered:

> When the vehicle got here it wasn't finished. ... so we had a lot of work to do down here, it was almost like we had to finish building it.[52]

And as Deputy Director of Space Shuttle Projects Management at Kennedy, Samuel Beddingfield, also recollected:

> Well when the shuttle got here, and this has been kind of a tradition, an unfortunate tradition, that when the Rockwell people deliver a spacecraft down here to be launched its never finished. It has a lot of work to be done on it, even though they claim that its finished. Now when that one came in the tiles were a huge problem, the thermal protection system tiles. We lost a lot of them in transit, just flying it across the country. ... It ended up that we had to replace almost all the tiles on the whole vehicle and the work was not very well done, they had a lot of sloppy workers and there was a lot of other things that had to be tweaked. The landing gear was not working right, the brakes were not working right. So we practically rebuilt the thing down here; so it was a long time after it was delivered before the first flight and part of it is just being absolutely concerned with checking it out, making sure everything works. But a large part of it was that it just wasn't finished being built. They did the same thing on the Apollo space vehicle.[53]

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51 Herb Yarbrough, interview with the author, September 5, 1995.

52 John Tribe, interview, with the author, July 28, 1995.

53 Samuel Beddingfield, interview with the author, July 31, 1995.

In a tremendous effort to complete the work on Columbia in time for a November 1979 launch, NASA moved over 2 000 workers from Palmdale, California to Kennedy at a cost of over $1.8 million. A huge complex of temporary accommodation and facilities was established at Kennedy to house all the workers, who were working seven days a week, three shifts a day, to finish building Columbia. In addition, NASA also hired every man and women in Bravade County that wanted to work on the space shuttle, to work with the application of the thermal protection tiles, because it was a such a labour intensive operation. Included in that workforce was over 320 high school graduates and college students on their summer vacation.[54] John Halsema recalled his experiences as a temporary technician, hired to install the thermal protection tiles.

> When I started working ... we were in a big push to get the shuttle finished. ... We started working a tremendous amount of hours ... after my initial training, we started working 12 hours a day for five days a week and 8 hours a day on Saturday and Sunday. ... We had to be at work at five in the morning and we got off at 5:45. ... I think everybody at that period of time had a real personal feeling about working on the space shuttle. Most of the people that were hired temporarily here, grew up here and so they were in the same situation I was, they had [grown up] watching rockets take-off. ... All of us were young, in our late teens to early twenties ... there were a few of the old hands that had been technicians during the Apollo program and they were kind of the corporate memory and we got to

54 John Tribe, interview, with the author, July 28, 1995; R. Jeffrey Smith, 'Shuttle Problems Compromise Space Program,' ***Science*** 206, (November 23, 1979) , pp 910-914; Arlen Large, 'America's Space Shuttle Lemon,' ***Wall Street Journal*** (January 31, 1980) , p 14; Deborah Kyle, 'The Space Shuttle: Ahead of Its Time - Or Biding It?,' ***Armed Forces Journal International*** (July, 1980), pp 44, 56; S. Diamond, 'NASA Wasted Billions, Federal Audit Discloses,' ***New York Times*** (April 23, 1986).

> hear what it was like during the big pushes during the Apollo era.[55]

For the temporary technicians, working on the shuttle was both an 'interesting and enjoyable' experience. Although the hours were long, for many it fulfilled their dreams of getting up close to a space vehicle. For the full-timers at Kennedy, however, getting the shuttle ready to fly was turning into a nightmare, as John Tribe recalled:

> Those were some black days, ... I wondered if we'd ever fly. It just seem like that every time we started to put things back together there would be another [modification], or another crisis would occur, so that we had to go and start taking it apart again.[56]

As detailed in chapter 6, technical problems continued to plague the programme through 1979 and 1980. By the end of March, 1979 it had become clear to NASA's higher echelons that the FY 1980 and FY 1981 budgets could not sustain the development programme. In April 1979, therefore, NASA officials went back to the Congress and the White House to inform them that the programme required an additional $270 million in FY 1980 and $200-250 million more in FY 1981. The date for the first launch was again delayed, tentatively put at the first quarter of 1980.[57]

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55 John Halsema, interview with the author, July 26, 1995.

56 John Tribe, interview, with the author, July 28, 1995.

57 John Fialka, 'U.S. Space Shuttle Program Has New Money Problems,' ***The Washington Star*** (May 2, 1979); 'NASA Will Tailor Shuttle Slip to DOD Needs, Seek Budget Hike if Required,' ***Aerospace Daily*** (May 3, 1979), p 15; Thomas O'Toole, 'Space Shuttle Money Pinch May Force Science to Back Seat,' ***The Washington Post*** (May 6, 1979) ; John Noble Wilford, 'Delay in Space Shuttle Facing Carter Review; Funds May be Raised,' ***New York Times*** (May 11, 1979).

> NASA finally confessed up to the problems they had. They had been sort of keeping them undercover and accepting the fact that they had to live with the smaller budgets that [the Carter] administration was placing on the shuttle. That got us in trouble with the Congress because two weeks before ... we had been up in the Congress testifying that we really didn't need any more money. ... When they found that we needed more money then that's when ... the shit hit the fan and the Congress became very very upset with NASA.[58]

Senator Adlai Stevenson (Democrat, Illinois), chair of the Senate subcommittee on Science, Technology and Space, expressed a major concern that NASA appeared to have discovered its $270 million shortfall rather suddenly, when only a month previously the agency had told the Senate that the programmes budget was sufficient. Representative Edward Boland (Democrat-Massachusetts), chair of the House Appropriations subcommittee on HUD-independent agencies, also remarked that 'NASA's credibility has been stretched a little thin' by the revelation of funding problems little more than a month after the regular budget hearings.[59] And Representative Larry Winn (Republican, Kansas) commented:

> After spending all these years travelling from one briefing on Shuttle status to the next, I feel like I have totally wasted my time. The visits gave me the confidence to go before my colleagues in the House of Representatives and fight for the necessary support to move this

58 Christopher Kraft, interview with the author, September 1, 1995.

59 John Fialka, 'U.S. Space Shuttle Program Has New Money Problems,' ***The Washington Star*** (May 2, 1979); 'NASA Will Tailor Shuttle Slip to DOD Needs, Seek Budget Hike if Required,' ***Aerospace Daily*** (May 3, 1979), p 15.

> program along. I can now see that it was a false sense of confidence.[60]

Indeed, the disclosure of funding problems led to a general crisis of confidence over NASA's ability to manage the shuttle programme. And despite NASA Administrator, Robert Frosch's claim that NASA's top management did not know about the enormity of the increases sooner because of 'institutional pride,'[61] both the Congress and the White House insisted on investigations into NASA shuttle management.[62]

Redemption.

NASA's profile on Capitol Hill plummeted after its request for additional funding and there was a growing concern within the agency about the rise in opposition to the shuttle. As Johnson's Director, Christopher Kraft recalled, it was a dangerous time for the programme.

> It was about the period [when]... we began to recognise that we had a large financial problem on our hands [that] NASA was almost in the position where they had to turn the program into an R&D program, as opposed to an operating vehicle. And go to just producing one vehicle and finding out what we could do with it: as opposed to producing a number of vehicles and making it

60 Larry Winn, quoted in Ken Hechler, ***Toward the Endless Frontier*** p 304.

61 'Frosch Sees 'Error in Judgement' in Timing of Shuttle Disclosures,' ***Aerospace Daily*** (July 5, 1979), pp 20-21.

62 Letter to Senator Howard Cannon from Robert Frosch, reprinted in ***Aerospace Daily*** (May 14, 1979), p 68; Memorandum to Robert Frosch from Alan Lovelace, reprinted in ***Aerospace Daily*** (May 14, 1979), p 69; 'Carter Asks for Space Shuttle Briefing,' ***Aviation Week and Space Technology*** (August 6, 1979), p 21.

> the work horse of the space program, which was what it was originally designed to be.[63]

NASA considered that the agency alone would not be able to get the increases through Congress. What it needed was the support of the Office of Management and Budget and the President.[64]

Paradoxically, given Carter's election rhetoric, it was the military potentials of the shuttle and space in general, that had become significant to the White House. In mid-1977, Carter had established an Inter-agency Space Program Coordinating Committee to draw up various space policy options. The committee, headed by Carter's Defense Secretary, was made up of members from: NASA, the DOD, the State Department, the Central Intelligence Agency, the Office of the President's National Security Advisor, the Office of Science and Technology, the Department of Agriculture, and the Department of Commerce. By early 1978, the committee had reached its conclusion and a draft policy document had been sent to the White House for Carter's approval. The policy document sparked controversy among some civilian agencies and within Congress, because of its emphasis on the military and intelligence utilization of space. Many argued that if the policy directive were approved then the DOD would have greater control over

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63 Christopher Kraft, interview with the author, September 1, 1995.

64 Memorandum to Curt Hessler, Associate Director OMB, from Alan Lovelace, Duputy Administrator, n.d (NASA History Office Archives, Washington DC).

civilian space activity. Nevertheless, in October 1978, Carter authorized the space policy directive and a number of inter-agency committees were established to ensure both civilian and military exploitation of the shuttle.[65]

Combined with issues stemming from the fleet size debate, as shown above, the shuttle became further embroiled with a military agenda. As the issue of funding reached the highest echelons of power, the density of this entanglement increased. NASA Administrator, Robert Frosch had originally proposed that the $270 million required to complete the shuttle's development could be transferred from NASA's production budget, as was done in 1977.[66] The Pentagon, however, were not in agreement. Shifting funds from production to development would delay the delivery of orbiters 3 and 4 (Discovery and Atlantis) which had serious implications for the launching of DOD reconnaissance satellites. Discovery and Atlantis were designed to be much lighter orbiters than Columbia and Challenger. Under Secretary of Defense for Research and Engineering, William Perry, told Congress that if they approved the funding increases, then NASA's schedule for development of the

65 Press release from the Office of the White House Press Secretary, on the Presidents Space Policy, October 18, 1978 (Marshall Space Flight Center Archive, Huntsville, Alabama); Craig Covault, 'Unified Policy on Space Readied,' ***Aviation Week and Space Technology*** (January 2, 1978), pp 14-16; Craig Covault, 'Space Policy Mandates US Leadership,'***Aviation Week and Space Technology*** (October 16, 1978), pp 24-26; Craig Covault, 'Debate on Space Policy Heats,' ***Aviation Week and Space Technology*** (February 5, 1979), pp 12-13; Craig Covault, 'Space Policy Discussion Stresses Solid Goal Need,' ***Aviation Week and Space Technology*** (February 19, 1979), pp 52-54.

66 Thomas O'Toole, 'Space Shuttle Money Pinch May Force Science to Back Seat,' ***The Washington Post*** (May 6, 1979); John Noble Wilford, 'Delay in Space Shuttle Facing Carter Review; Funds May be Raised,' ***New York Times*** (May 11, 1979).

first four orbiters would meet DOD launch requirements, but with very little margin. The DOD needed the lighter orbiters to launch their heavy spy satellites into a polar orbit, and they needed Atlantis by December 1983: Atlantis's delivery date was September 1983.[67]

Late in 1979, Carter declared his support for NASA's request for extra funding in FY 1980 and FY 1981.[68] NASA claimed that it was surprised by the Carter Administration's decision to place a higher priority on adherence to the planned launch schedules for certain DOD shuttle missions than on the objective of holding the NASA budget within previously approved levels. Key sources within the Pentagon professed that the key question, which convinced Carter to push Congress for the extra funding was the availability of the shuttle to launch intelligence missions needed to verify Soviet compliance with the second round of the Strategic Arms Limitation Talks (SALT II), which was being debated in the Senate at the time.[69]

> It was at the time of the SALT talks and agreements and the Carter Administration began to use the shuttle as a political tool, an international political tool, to threaten the Russians with the capabilities the shuttle would have to intervene in a hot war and as a spy tool. ... It was after one of those very detailed

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67 'Shuttle Must Have All Funds Required to Meet DOD Needs,' ***Defense/Space Daily*** (June 6, 1979), p 177; 'Frosch Sees Shuttle Supplement of Several Hundred Million Dollars,' ***Aerospace Daily*** (October 19, 1979), pp 237-238.

68 Craig Covault, 'Administration Backs Shuttle Fund Rise,' ***Aviation Week and Space Technology*** (September 17, 1979), pp 22-23.

69 'Administration Vetoed NASA Plan to Slip Shuttle Further,' ***Aerospace Daily*** (September 20, 1979), p 36; Alton Marsh, 'SALT Support Tied to Defense Gains,' ***Aviation Week and Space Technology*** (August 6, 1979), p 20.

> meetings in Switzerland ... that he came back to this country and became aware that the shuttle was well behind schedule and well under budgeted. And so he said what do you need to fix it? We told him.[70]

> We were under a lot of cost pressure ... and I think that was about some of the time when some of the weapons control programs with the Russians were being initiated. ... It appeared that the plans were for the shuttle to orbit satellites that could monitor what the Russians were doing in connection with these treaties. So some of our cost problems went away during the Carter administration because of that.[71]

NASA had maintained that they were unaware of the implications of SALT II on the delay of orbiter production.[72] But by end of 1979 the agency had no problem with using SALT II to reinforce its position. In September it had become clear to NASA that the first launch would slip further from April 1980 to September 1980. In a letter to Carter, Frosch was eager to make it clear that:

> ... the schedule adjustment will not [sic] affect the important initial SALT related launch schedule for the shuttle in early 1983, and all subsequent national security related missions.[73]

Estimates of funding over and above the planned spending limits ranged from $200 to $300 million for FY 1980 and $400 to $450 million for FY 1981. Frosch told Carter:

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70 Christopher Kraft, interview with the author, September 1, 1995.

71 Robert Lindstrom, interview with the author, August 17, 1995.

72 'Administration Vetoed NASA Plan to Slip Shuttle Further,' ***Aerospace Daily*** (September 20, 1979), p 36.

73 Memorandum to President Carter from Robert Frosch, September 11, 1979 (NASA History Office Archive, Washington DC).

> We believe that a general commitment now should be sufficient to assure the Congress that the Administration is still fully committed to use the shuttle for the important SALT-related launch in early 1983.[74]

On November 14, 1979 Frosch and Carter had a private meeting to discuss the status of the shuttle. At this meeting Carter again reiterated his support for the programme and its continuation towards fully operational status.[75] After that meeting, Frosch told Congress that the driving force behind keeping the shuttle on schedule was the SALT II agreement.[76] Prior to the meeting, the White House had conducted a shuttle review, which involved the Office of Management and Budget, the Office of Science and Technology Policy, and the National Security Council. They all reaffirmed the need for the shuttle programme to continue as originally planned because of SALT II. One high level observer noted that the most significant ramification of the review was the substantial change in position of the Office of Management and Budget.[77]

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74 ***Ibid.***

75 Letter from President Jimmy Carter to Bob Frosch, November 26, 1979 (NASA History Office Archive, Washington DC); Press briefing on Robert Frosch's conversation with President Carter regarding the space shuttle, November 14, 1979 (NASA History Office Archive, Washington DC).

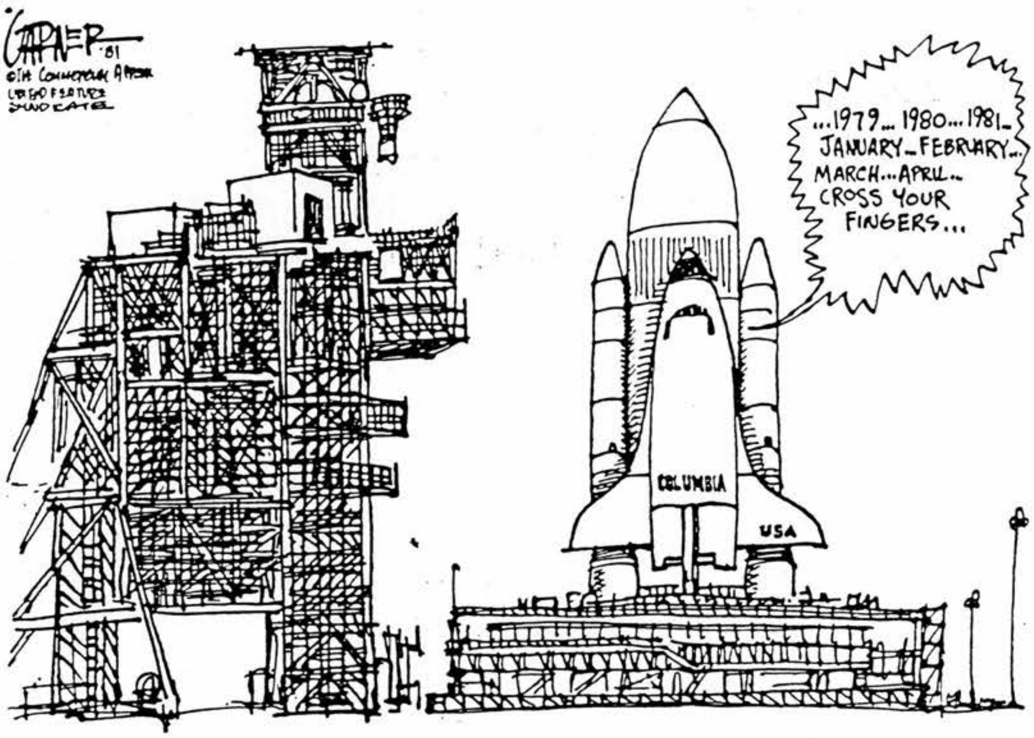
76 Thomas O'Toole, 'NASA Head Says Carter Will Fully Back Shuttle,' ***The Washington Post*** (November 15, 1979) ; John Noble Wilford, 'Carter To Seek Aid For Space Shuttle,' ***New York Times*** (November 15, 1979).

77 Craig Covault, 'Carter Backs Shuttle Fund Rise,' ***Aviation Week and Space Technology*** (November 19, 1979), pp 16-18.

In 1972, NASA claimed that the first orbital flight would take place in 1977. By 1973, this had moved forward to 1978. As the programme progressed the launch date slipped further and further into the future. March 1979 came and went. Then it was September 1979, December 1979 and then the spring of 1980. In mid-1980 it became clear to NASA Administrator, Robert Frosch, that the shuttle would not be launched before the next presidential election and he announced a new launch date of March 1981.[78] Thus, it was President Ronald Reagan, not President Carter, that would gain the "political capital" from a "space spectacular".

78 'Frosch Reaffirms Goal of March STS-1 launch,' ***Roundup*** (August 8, 1980), p 1.

Birmingham Post-Herald
Apr. 10, 1981



Chapter 9

Transitions

> When the system attained to a certain degree of development, it had to root up this ready-made foundation, which in the meantime had been elaborated on the old lines, and to build up for itself a basis that should correspond to its methods of production.[1]

Print 9:1 captures a moment in time during a readiness test for the inaugural flight of Columbia. The test was part of a series that took place some months before Columbia's first flight, which eventually took place in April 1981. Together, the tests marked the end of the long process of design, development and fabrication. The technology had taken on physical form. It existed as an object and was ready to make the transition from conditions of construction to conditions of use. The boundary between creation and operation was, nonetheless, more opaque than this. Conditions of use were as significant during construction, as conditions of construction were during use. However, whereas the previous chapters principally addressed the former, the central focus of this penultimate chapter is on the latter.

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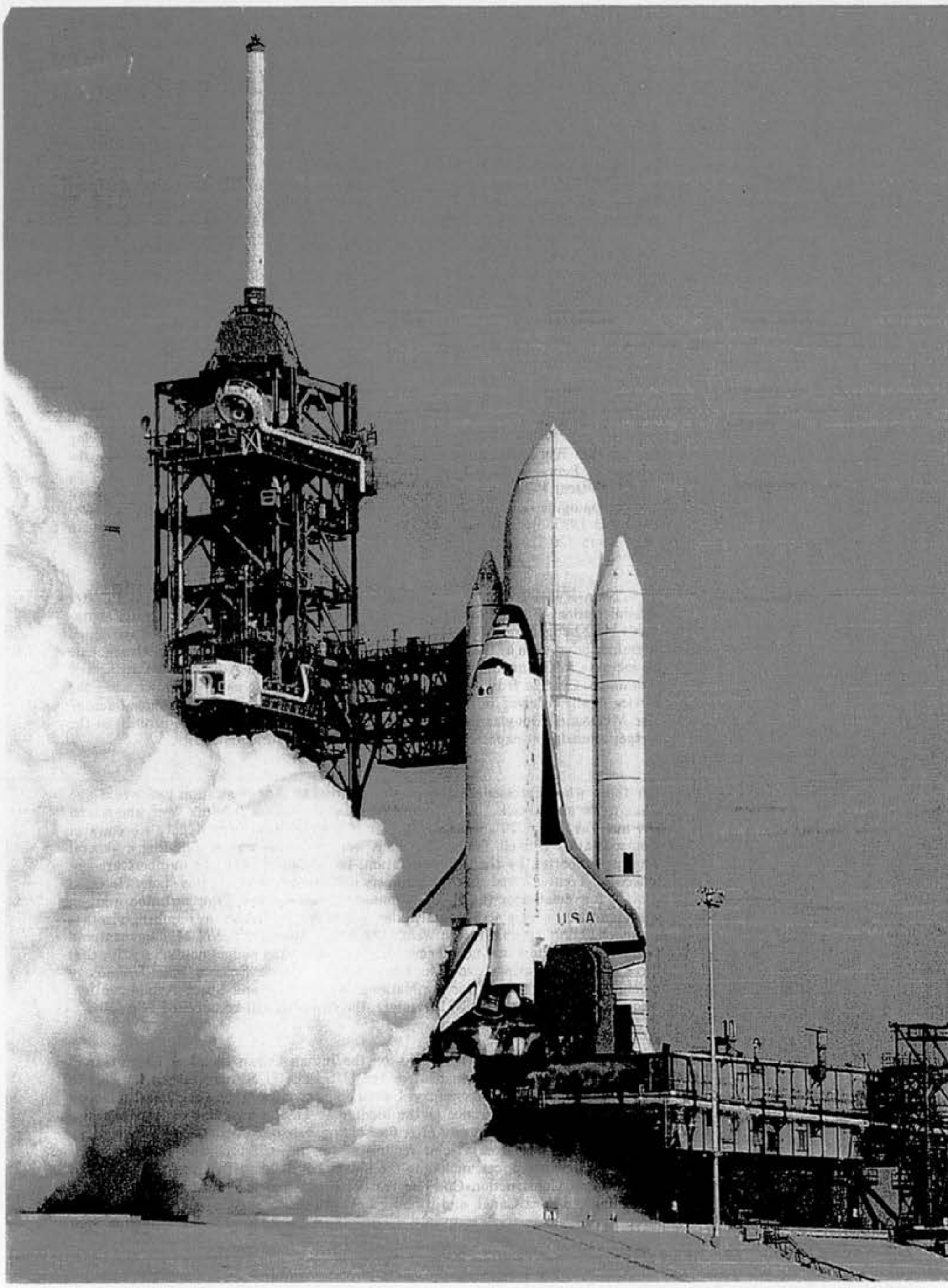
1 Karl Marx, ***Capital, A Critique of Political Economy: Vol 1, The Process of Capitalist Production*** Samuel More, Edward Aveling, (trans), Frederick Engles, (ed) (Chigaco, Charles H.Kerr and Co, 1919), p 417.



Source: Edward Kolcum, 'Shuttle Engine Firing Successful,' ***Aviation Week and Space Technology*** (March 2, 1981), p 16.

Idioms From the Airliner Lexicon.

Based on the premise of a "mass space market", the essence of the shuttle revolution was economies of scale. What this meant in operational terms, was a radical shift in the way NASA was organized and the way in which that organization had worked. Conceived as a routine operational vehicle, the shuttle was to compel parts of NASA to face a new environment; an environment geared to providing a regular service.

Yet, regular, routine, or mundane work, was not part of the perceived practice of NASA's space divisions.

> [Routine operations] were not very well known. We had people who had been involved with aircraft, ... but the NASA culture was not into operations period. NASA was excellent at planning and operating on a mission basis. They didn't have experience in operating on a continual basis with turning vehicles around, processing them, getting that vehicle ready to fly again [and] having another vehicle behind that.[2]

Before 1970, NASA had built a reputation for being an innovative organization, working largely in realms of the unknown and pushing forward the boundaries of both knowledge and machinery. Assimilated into this image after 1970, was a "NASA speak" that voiced idioms from the airliner lexicon. Customer service, customer demand, the marketplace, load factors, and frequent turnaround, all became part of a discourse exhorting the shuttle revolution. In the "new politics" of space, analogies with

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2 Herb Yarbrough, interview with the author, September 5, 1995.

the airlines were often used to accentuate the shape of things to come.[3]

> George Low [NASA Associate Administrator] ... left us a terrible heritage. ... He said we have to take a Frontier Airlines approach to shuttle operations. Now, Frontier Airlines was a little airline out west that had cheap rates. ... Well it gave the public the impression that flying the shuttle was like flying an airline.[4]

Unlike NASA's previous human space programmes, where the agency designed the requirements, developed the vehicle and served as the customer, with the shuttle, NASA would have to provide a flexible, on-going service, for people other than itself.[5] Although ideas of turning the shuttle over to private hands had been examined, NASA was aware that, at least in the short term, it would be responsible for shuttle operations.[6] Thus, in the early to mid-1970s, members from both NASA and Rockwell contacted some of the major US airline companies in an effort to accumulate expertise in operational procedures.[7]

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3 John Yardley, 'To the First Launch,' ***Astronautics & Aeronautics*** (February, 1979), pp 28-34, 72; William Gregory, 'Shuttle Open's Door to New Space Era,' ***Aviation Week and Space Technology*** (November 8, 1976), pp 39-43; 'Kennedy Center Stresses Customer Service,' ***Aviation Week and Space Technology*** (November 8, 1976), p 122.

4 George English, interview with the author, July 26, 1995.

5 John Yardley, 'To the First Shuttle Launch' ***Astronautics & Aeronautics*** (February, 1979), pp 28-72.

6 The Boeing Corporation had expressed an interest in becoming the private owner/operator of the shuttle fleet in the mid-1970s and had been conducting detailed studies on the profitability of a private shuttle and the transition process from government to private operations. NASA expressed a preference for turning the management of virtually all shuttles operations over to private hands by 1982, thus allowing the agency to remain a pure research and development organisation. Chester Lee, (Interview, May 2, 1995); Craig Covault, 'Boeing Eyes Private Shuttle Operation,' ***Aviation Week and Space Technology*** (October 2, 1978), pp 23-25; Craig Covault, 'Shuttle Management Shifting to Operations,' ***Aviation Week and Space Technology*** (December 21, 1981), p 15-17; 'Investment Firm Unit Considers Private Buy of Space Shuttle,' ***Aviation Week and Space Technology*** (January 4, 1982), p 23.

7 Ted Carey, interview with the author, July 22, 1995.

> I can remember that we brought in all the airlines, ... Delta, American, United, to tell us how they operated; ... and we conceived the shuttle as being like an aircraft, you bring it back, you maybe change-out one or two things, you check-it-out and you go back. ... Much like an airline, you land and you take-off. ... We were very definitely, at that time, modelling after the airlines.[8]

> Realistically or not, the concept was ... flying 60 missions a year. In other words every two weeks, turning them around and flying again and that concept drove us for quite some time in how we would do the operations. ... So my job was to start thinking about how we might do the operations on a on-going basis and in an economical fashion, which meant if you were flying every two weeks you had several orbiters ... in orbit at the same time and you had have crews handling that. ... We made a number of visits to airline control Centers ... and talked to airlines ... and had a number of study contracts, of how they operated compared to what we were doing. How they controlled the scheduling and the overflights ... the repairs, the turnaround time. ... So we looked at control Centers where the Administrator, the Program Director and all that, had all the data coming in, you made contact with all your managers, like the airlines do with all their airline planes; like how many were down, how many did you bring up last night. We talked to the airlines about it ... because they were as close to what we were after than anybody.[9]

But, in the end, NASA was unable to gain much experience, or knowledge from the airlines that it found applicable.[10]

> There's some things that you could learn from airline maintenance, but the airline maintenance people that came in to look at the operations, I think, really learnt more to help their operations from what we were operating than we

8 Bill Sneed, interview with the author, August 21, 1995.

9 Chester Lee, interview with the author, May 2, 1995.

10 LeRoy Day, interview with the author, June 26, 1995; Ted Carey, interview with the author, July 22, 1995.

> learnt from them. [The shuttle was] just a different beast.[11]

> The one I remember was American Airlines ... when we were trying to figure how to run the shuttle ... [but] it's not an aeroplane and you can't operate it like and aeroplane ... I don't think we learned anything out of that.[12]

Nevertheless, the idea that the shuttle could be run along similar lines as a commercial airline had become ingrained. Johnson's Director, Christopher Kraft, commented in 1978:

> If we're going to make this thing a routine operation, it's got to go in a more matter-of-fact manner, more like an airline operation, than we've seen in the past.[13]

James Abrahamson, NASA's Associate Administrator for the Office of Space Transportation System Operations, commenting in 1981:

> [W]e have to make a major effort ... to simplify and improve our procedures so that we can have a reliable and repeatable airline-type operation.[14]

The impression was of a future with clean, reusable and routine space travel.

> If you look back at the pictures, at the artist's styling of what it was going to be like, [they] showed an orbiter sitting in this sterile [orbiter processing facility], glistening floors, one little access stand and about two technicians

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11 George English, interview with the author, July 26, 1995.

12 Francis Hoban, interview with the author, May 15, 1995.

13 Christopher Kraft, quoted in 'Kraft Sees Growing Role of Private Industry in Space' ***Roundup*** (Houston, Texas, NASA, Johnson Space Center, September 29, 1978), p 4.

14 James Abrahamson, quoted in, Craig Covault, 'Shuttle Management Shifting to Operations,' ***Aviation Week and Space Technology*** (December 21, 1981), p 16.

> wandering around. It was totally unreal, but unfortunately we believed the propaganda.[15]

Planning for the Spaceliner.

Early in 1974, NASA began to prepare its organization for the change over from expendable launch vehicle to shuttle operations. The Office of Manned Space Flight was reorganized in a new Office of Space Flight that took control over both the shuttle and expendable launch vehicles. NASA saw this reorganization as indicative of the seriousness that it placed on shuttle operations, because it removed the traditional split between human and non-human space flight; an organizational structure that was no longer thought pertinent to shuttle operations. Other key elements of NASA's reorganization were the establishment of a Deputy Associate Administrator for Operations and a Space Transportation Systems Operations Directorate, both housed in the new Office of Space Flight.[16] This structure remained in place until the budget fiasco in 1979, which influenced further management changes. The Office of Space Transportation Systems was renamed the Office of Space Transportation System Acquisition and was given total control over shuttle operations, scheduling, pricing,

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15 John Tribe, interview with the author, July 28, 1995.

16 James Fletcher, special announcement distributed to all NASA centers, March 5, 1974 (NASA History Office Archive, Washington DC); 'NASA Reorganizes Manned Space Flight Office,' ***Aviation Week and Space Technology*** (September 29, 1975), p 19; John Yardley, ***Operating the National Spaceline***, Draft paper for AIAA presentation, January 28, 1976 (NASA History Office Archive, Washington DC).

launch service agreements, and the Spacelab program. NASA considered that this reorganization would streamline shuttle management by first, allowing the Associate Administrator for Space Flight, John Yardley, to focus attention on getting the shuttle built and flying; and second, by centralizing all shuttle services in a single user-orientated organization.[17]

Nevertheless, the critical issue was labour. NASA knew that it could not continue to conduct operations the way it had on the Apollo programme, where there was an enormous ground support team.[18] An issue Kennedy's Acting Director, Miles Ross, commented on in connection with the Space Flight Operation Ad Hoc Committee.

> This group must be very aware that the Space Transportation System [STS] will not command the space transportation market place by NASA decree but must be cost effective, flexible, and responsive. The proposed Center responsibility charts in the report and the Marshall Space Flight Center comments on the report indicate overlaps of Center responsibilities that could result in a very complex, expensive, and inflexible inter-Center interfaces. It is the emerging feeling among shuttle critics that "with 3 NASA Centers and Headquarters elements involving 30,000 people preparing for an STS operation, an operation involving fewer than 30,000 people is not likely to result." This new office must be very aware that good operational

17 'New Shuttle Admin Office User-oriented' ***Roundup*** (Houston, Texas, NASA, Johnson Space Center, October 19, 1979), p 1; 'Lunney Acting STS Chief of Operations' ***Roundup*** (Houston, Texas, NASA, Johnson Space Center, November 30, 1979), p 1.

18 Chester Lee, interview with the author, May 2, 1995.

> practice, the Congress, and the users will demand a less expensive, more flexible operation.[19]

Regardless of shuttle operational requirements, NASA was shedding civil service employment on the direction of the Office of Management and Budget as part of the agency's overall budget cuts. NASA in-house employment had steadily declined from 33 929 in 1969 to 23 779 in 1978, a decrease of almost 30 per cent.[20] However, the estimates of NASA and contractor labour for shuttle operations, uniformly rose with the machine's complexity.

> Well it's the thing that we call the marching army. ... For reasons that aren't quite clear to me, more is better in NASA. And a friend of mine, ... he has done some work on processing parts of the shuttle down at the Cape [Kennedy]. For instance, the fuel cells, the fuel cell's trail through that organization is like a spider's web. ... It's bizarre in some cases. ... One of the fellows on the shuttle took us down to Michoud and we were looking at tanks being manufactured and he said to me, 'on this tank there are 100 000 visual inspections ... *100 000 visual inspections* is an enormous waste.' He was absolutely correct.[21]

All three of NASA human space flight Centers were gearing up for shuttle operations during the mid-1970s. Concern about how shuttle flights would effect activities at Mission Control was a big issue for Johnson.[22] But for

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19 Letter from Miles Ross, Acting Director KSC, to John Yardley, Associate Administrator for Manned Space Flight, January 9, 1975 (Kennedy Space Center Archive, Florida).

20 Ihor Gawdiak, Helen Fedor, ***NASA Historical Data Book: Volume IV*** p 59.

21 Francis Hoban, interview with the author, May 15, 1995.

22 'JSC to Ask Think Tank to Study Center Roles,' ***Roundup*** (Houston, Texas, JSC, August 18, 1978), p 1.

Kennedy, planning and working on concepts for shuttle operations was the central issue, because the level of activity on the ground, required to prepare the shuttle to fly, would be an order of magnitude of what would be demanded once it lifted-off.[23]

In the early days of human space flight most of the activities during launch preparation were merely an extension of the factory. All of the procedures for both the factory and the launch site were written at the factory. So the design, test, fabrication and launch was almost totally under the control of the factory. The continuous and routine nature of the shuttle, however, made launch and turnaround procedures Kennedy's responsibility; even when hardware and software interfaces with shuttle components and ground support equipment were designed elsewhere.[24] Thus, Kennedy had to establish a whole new set processes, procedures and management control systems.

> In the early 1970s we spent our time planning out how we were going to get this thing ready to fly, because it was a major new thing. ... So we tried to mount everything we knew about boosters, spacecraft, aircraft and overall maintenance to figure out how we were going to process this thing.[25]

NASA and contractor employees at the Kennedy recognized early that the shuttle was a technological

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23 Robert Sieck, interview with the author, August 1, 1995.

24 Ted Carey, interview with the author, July 22, 1995; Craig Covault, 'Cape Shuttle Capabilities Broadened,' ***Aviation Week and Space Technology*** (October 13, 1975), pp 40-43.

25 Ted Carey, interview with the author, July 22, 1995.

regime unique to its own operations. NASA's attention to considerations of continual operations may have long been a traditional part of aircraft design and development, but in the design and development of space vehicles, this had not been the case. Thus, Kennedy consistently pushed for a new dimension to research and development so that operational logistics would be an early emphasis of a shuttle design.[26] As Robert Sieck, Kennedy Director for Shuttle Operations, recollected:

> Our challenge ... was to make sure [the shuttle] was compatible with being checked out, inspected from one mission to the other, because this was a new concept. ... Before we built everything brand new and flew it and threw it away. ... So we wanted to develop a system that would not only carry the payload, but also would be maintainable during the turnaround activity.[27]

And as Rockwell (Kennedy Div) engineer, John Tribe also recalled:

> When we were still trying to decide what configuration [the shuttle] should take ... my primary purpose ... was to get the operational influence into the design. ... I had been down on the op's end for ten years and knew what we ought to have on a vehicle that would permit easy maintenance, fast turnaround; make it a useable vehicle and not just some analysist's design of what they think it ought to be. ... My first five years on the orbiter was really working those interfaces. Going back, fighting to get specific

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26 Letter to Deputy Associate Administrator, Aeronautics from G. Merritt Preston, May 1970 (Kennedy Space Center Archives, Florida); Letter to NASA Headquarters, Acting Administrator for Advanced Research and Technology from G. Merritt Preston, May 7, 1970 (Kennedy Space Center Archives, Florida); Letter to Dale Myers from Kurt Debus, July 16, 1970 (Kennedy Space Center Archives, Florida); Letter to Acting Director, Space Shuttle Program from G. Merritt Preston, August 20, 1970 (Kennedy Space Center Archives, Florida); Letter to Director of Launch Operations from G. Merritt Preston, September 4, 1970 (Kennedy Space Center Archives, Florida); Letter from Merritt Preston to the Director, Space Shuttle Technology Program, 1971 (Kennedy Space Center Archives, Florida); John Tribe, interview with the author, July 28, 1995.

27 Robert Sieck, interview with the author, August 1, 1995.

design criteria that would make it easier for us down here in the field.[28]

Routine operations necessitated ease of access to all the various sub-systems that would require maintenance, repair, replacement, checkout and pre-flight testing. The position of each sub-system within and on the shuttle, were thus important considerations. The technicians that would swarm the shuttle during its preparation for launch and again after its return flight, had to be able to work on their specialised sub-system with the least hinderance; either from other technicians or from other sub-systems. Access routes along the vertical and the horizontal, and the position of each sub-system in relation to other sub-systems within the same locality, were critical design issue. If a particular sub-system needed to be replaced, then the last thing Kennedy wanted was another sub-system right in the way.[29]

The most critical changes for Kennedy, however, was in making the transition from preparation and planning with expendable vehicles to preparation and planning with a reusable vehicle. With the shuttle, Kennedy was introduced to a whole new problem; that of "technological life". Up until the shuttle, all of NASA's operational experience in human space flight had been with launch vehicles and

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28 John Tribe, interview with the author, July 28, 1995.

29 John Tribe, interview with the author, July 28, 1995; Robert Sieck, interview with the author, August 1, 1995; Lee Solid, interview with the author, July 26, 1995; Ted Oglesby, 'Selected Apollo/Saturn Operational Problems,' 1972 (Kennedy Space Center Archive, Florida).

spacecraft that were brand new and flown only once.[30] Typical missions during the early years lasted, at most, for only a few days; and each individual flight, was regarded as a unique event, subject to its own set of risks, problems and enigmas.[31] Concerns about technological life were, therefore, limited to the life of the mission. Nevertheless, as Rockwell Engineer (Kennedy Div), Ted Carey, explained:

> That all changed with shuttle, because theoretically we were going to fly parts of the thing for 20, 30 or 40 years and that had not been designed for; ... there wasn't anything set up to monitor how many cycles, or how much operating time, or how many launch environments or anything like that. So that was totally driven by this new, strange, reusable machine.[32]

Technological life, reliability, safety, and age were all inextricably linked. Engineers at Kennedy were sure that the 'rate of failure' would increase as the hardware got older.

> The equipment we deal with is older ... and older systems don't mature with age, they just get older.[33]

The pressing problem was knowing when a particular piece of hardware was going to 'run out of life:' at what point would it fail. Cooperation with the other NASA Centers and development contractors was a necessary part of this

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30 Robert Sieck, interview with the author, August 1, 1995.

31 Howard McCurdy, ***Inside NASA*** pp 72-73, 142-143.

32 Ted Carey, interview with the author, July 22, 1995.

33 Robert Sieck, interview with the author, August 1, 1995.

process. A mass of data on technological life was being generated by the shuttle's development engineers via a range of testing methods. Certain parts were tested to destruction; in others deliberate flaws were introduced to discover if the testing procedures picked them out; and system tests within simulated operational environments, over specified "life spans" also added to the data set.[34]

However, the problem of technological life was further compounded by the enigma of "technological history". The notion that once a particular system was installed and started to fly, it would develop a unique history shaped by a myriad of different events. In this case, each serial number, on every piece of technology, would actually represent the different experiences of that particular system. Technological life, therefore, would not only be determined by system design, but by the manufacturing process and particular flight experiences. Finding a method to track the history of each sub-system was, therefore, of the utmost importance. The nature of technology demanded a very fine set of test requirements for pre-launch checkout, but all of those tests would not necessarily be applicable for every turnaround; it would depend upon the history of

34 Norman Chaffee, interview with the author, September 6, 1995; Lee Solid, interview with the author, July 26, 1995;Ted Carey, interview with the author, July 22, 1995; Robert Sieck, interview with the author, August 1, 1995.

each part. As an operational procedure, this whole area was brand new to NASA.[35]

Building for the Spaceliner.

The goal of achieving rapid turnarounds with reusable technology and less labour, thus, drove a total revision of launch operations philosophy, with change centred on widespread automation and computerization.[36] The concept was to have the shuttle in direct computer connection to the Launch Control Center, so that engineers could monitor what was going on in the spacecraft at all times. The original concept called for a central monolithic mainframe approach, similar to that used on Apollo. But members at Kennedy considered that such an approach would mean that the checkout programmes would have to be run serially, which could frustrate the goal of a 160 hours turnaround time. Instead, Kennedy proposed a system that consisted of a collection of minicomputers that could run in parallel. This, it was argued, would speed up the turnaround process and avoid conflict between component engineers and some central memory allocations committee, over working space in the central computer.[37]

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35 ***Ibid***; Mike Kinnan, research and technology objectives and plans, Form 1417A, December 1977 (Kennedy Space Center Archive, Florida).

36 Craig Covault, 'Countdowns Revised for Space Shuttle,' ***Aviation Week and Space Technology*** (October 1, 1979), pp 58-64.

37 James Tomayko, ***Computers in Space: Journeys With NASA*** (Indiana, Alpha Books, 1994), chapter 3.

The concept that emerged was the launch processing system; a computer network that linked hundreds of components and test circuits to a central data sub-system, which consisted of two dual Honeywell 66/80 central processing units sharing a megaword of memory, and 172 disk drives with 30 billion bytes capacity; and a checkout, control and monitor sub-system, which consisted of 41 Modular Computer Inc., minicomputers (MODCOMP 11/45), sharing a common 64K-word, high-speed pipeline memory to communicate with each other. The data would then be displayed on consoles in the Launch Control Center and the Firing Rooms. The job of the central data sub-system was to store data on test procedures, vehicle processing, a master programme library, historical data, pre and post test data analysis and other vital information. Whereas the control monitor sub-system, would conduct the actual turnaround and launch processing.[38]

> I think that we made a great deal of progress when we did the launch processing system. We realized that we did not have enough, a good enough way to transmit what was going on at the pad back to the firing room and when we developed the common data buffer for the launch processing system that was a big process to do that. We could know a great deal more about what was going on a great deal quicker. We developed the computer to computer network rather than having to go through different relay logic waiting for a relay to click in an another relay to click in. ... We had computers, of course, in Apollo, but

38 William Bailey, 'Launch Processing System: Concept to Reality,' Norman Chaffee, (ed) ***Space Shuttle Technical Conference: Part 1*** pp 532-538; ***National Space Transportation System Reference: Volume 2, Operations***, September, 1988 (Kennedy Space Center Archive, Florida); 'Usable Launch Data Elements Delivered,' ***Aviation Week and Space Technology*** (November 8, 1976), p 83.

> they were very old ... and we realized very quickly there was no way we could make the shuttle work using that kind of computer.[39]

In contrast to previous practice, where the hardware was selected first and then the software was built to fit a "committed-to" system architecture, with the shuttle Kennedy began work on the software first. The Ground Oriented Aerospace Language (GOAL) programme had been under development since 1969, using data and experience accumulated from the launch tests and firings conducted on the Apollo/Saturn launch vehicles and spacecraft. Due to its near-English terminology, Kennedy considered that the language would be suitable for shuttle operations, because it would be easily learned by tests engineers.[40] Though, a lack of software specialists at Kennedy meant that IBM had to be enlisted in May, 1974 to provide systems engineering and software development support.[41]

> We had a whole bunch of test procedures written in English. ... Most of them written by experienced ground processing engineers, ... but then we were going to execute those procedures with software. The first decision we had was were we going to let those guys write them in English and then get some software specialists to come in and convert them into software language ... or were we going to teach the systems engineers, some of them fairly old, software application language. We decided to do the latter and then let software specialists in to help them with

39 Samuel Beddingfield, interview with the author, July 31, 1995.

40 Letter from G. Merritt Preston, Director of Center Planning, to Space Shuttle Program Manager, JSC, December 23, 1971 (Kennedy Space Center Archive, Florida).

41 Craig Covault, 'Cape Shuttle Capabilities Broadened,' ***Aviation Week and Space Technology*** (October 8, 1975), pp 40-43.

sticky issues ... That was a tough problem because a lot of guys ... didn't want to do that.[42]

Automation of turnaround and launch processing was, nonetheless, only one of many changes at Kennedy. Of crucial importance was the runway. Kennedy did not have a runway. On Mercury, Gemini and Apollo there was no need, but the shuttle was coming back and it needed somewhere to land. A runway did exist on the Air Force Base at Cape Canaveral and Kennedy did seriously examine the possibility of using it, but the Center found that it was more expensive to figure out a way of transporting the shuttle back to the Vehicle Assembly Building, than it was to build a new runway. The shuttle also demanded that Kennedy built some hanger-type facilities, which were eventually known as the Orbiter Processing Facilities.[43]

Nevertheless, the construction of facilities for shuttle operations at Kennedy was, as with all other aspects of the shuttle programme, shaped by the tight budget environment. This impelled the Center to base most of its planning on modifications to the Apollo/Saturn launch and turnaround facilities, rather than construct "shuttle specific" facilities.[44]

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42 Ted Carey, interview with the author, July 22, 1995.

43 Samuel Beddingfield, interview with the author, July 31, 1995.

44 Memorandum from R.H. Gray, to Director of Launch Operations, November 19, 1974 (Kennedy Space Center Archive, Florida); Letter from R.H. Gray to NASA Headquarters, October 20, 1975 (Kennedy Space Center Archive, Florida); 'Shuttle Flights From Cape to Use Modified Apollo Facilities,' ***Aviation Week and Space Technology*** (April 24, 1972), p 21; 'Shuttle Tempo Continues to Increase,' ***Spaceport News*** (January 9, 1978), pp 1,3-4.

> What we tried to do was reuse many of the Apollo facilities as we could. ... We modified the launch pad, we modified the Vehicle Assembly Building, a lot of buildings down in the industrial area were modified, we modified the Launch Control Center; all [of] those were reused.[45]

The type of modifications to be done, however, often provoked debate.

In the mid-1970s, modifications to the launch pad kindled a big controversy between Kennedy and Rockwell. Rockwell's approach was similar to that used on Apollo, where the launch pad was clean and the launch umbilical tower was attached to the mobile launch platform. A large service structure would then be rolled into place once the vehicle was in launch position. This was known as the 'tails north' approach because the shuttle would be taken out to the pad orbiter first, so its tail would face north. The Design Engineering Directorate at Kennedy, however, did not want to take that approach. It did not want a moving tower again, because it was perceived as too costly to maintain. Instead, Kennedy wanted to have the umbilical tower situated at the pad. With the shuttle the umbilical tower was not as fundamental as it was on Apollo, because most of the umbilicals were designed to come up through the tail service mask on the orbiter. Thus, only a minor amount of umbilicals were required on the tower itself. This approach was known as 'tails south' because the shuttle

45 Samuel Beddingfield, interview with the author, July 31, 1995.

would be taken out to the pad tank first, thus the orbiter's tail would face south. Kennedy eventually won the day and 240 foot of the nearly 400 foot Apollo launch tower was removed from the mobile launch platform and placed at the pad.[46]

As with most large construction project, though, small aberrations would domino very quickly. The discovery of requirements for significant ground facility modifications challenged Kennedy's managers because many were unearthed late in the programme.[47]

> When you have to rotate the shuttle, pick it up at the Vehicle Assembly Building, we wanted to be able to pick it up at the front, but structurally you can't do that. So you had to have these very large, huge beams that come down the side and the load can only be taken where the engine, the thrust of the engine, reacts into an aft bulkhead at the back, which means that we then had to have very large pieces of ground support equipment, which takes manpower to install, but it also takes maintenance. All of this stuff it adds geometrically.[48]

> Once we put the tower up at the pad and developed the mobile launcher, then [we started] getting the Air Force requirements; and they said we want to install our payloads at the pad rather than install the payloads prior [to assembly]. So then [we had] to start building ... the rotating service structure; and as you start building the rotating service structure, then everybody says gee that's a pretty good idea, that gives us good access. So it starts getting more and more requirements on the rotating service structure

46 John Tribe, interview with the author, July 28, 1995; James Jackson, interview with the author, July 12, 1995; Sammual Beddingfield, interview with the author, July 31, 1995; Mike Leinbac, interview with the author, July 27, 1995.

47 Craig Covault, 'Shuttle Shifting to Launch Processing,' ***Aviation Week and Space Technology*** (November 10, 1980), pp 17-20.

48 Samuel Beddingfield, interview with the author, July 31, 1995.

> and the next thing you know its too heavy, so you have to change the machinery that you got to move the thing.[49]

> We found out that we needed to use [a] water system to suppress the sound energy ... because there is about 35 mega watts of sound energy that comes out of the thing and it reflects off of these flat decks and back up into the vehicle, which could destroy the payload. So we found the most practical way to stop that was flood it with a lot of water and let the water absorb the sound energy. Well, you look around and say ok, what kind of water do we need? So we said alright, we need a flow rate of a million gallons a minute. You look around and try and find a pump that will pump a million gallons a minute and there are no pumps. So we said ok, we have to build a water tank that holds 300 000 gallons and we will dump that in 18 seconds. And so the stand pipe ... has to be fourteen feet in diameter ... so you end up building big water tanks with big pipes coming in just to use that water for 18 seconds. Those requirements, sometimes they end up at the last minute you don't know about them until you run the rocket engines.[50]

The task of operational planning at Kennedy was also hindered by: the fluidity of the shuttle's configuration, the shuttle's mass, the budget restrictions imposed by the Office of Management and Budget, and encroachments by Congress.[51]

> We were trying to lay out the design for all of the access stands in the [orbiter processing facility] and at the pad and [Rockwell] was continually moving access areas around ... doors, panels, [all] driving us crazy as we had to ...

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49 ***Ibid.***

50 ***Ibid.***

51 Letter to Space Shuttle Program Manager from R.H. Gray, Manager, Shuttle's Project Office, Kennedy, April 22, 1974 (Kennedy Space Center Archive, Florida); Letter to the Manager, Shuttle Projects Office, Marshall from R.H. Gray, Manager, Shuttle's Project Office, Kennedy, June 11, 1974 (Kennedy Space Center Archive, Florida); Memorandum to Director of Launch Operations from R.H Gray, Manager, Shuttle's Project Office, Kennedy, November 19, 1974 (Kennedy Space Center Archive, Florida); Memorandum to Director of Design Engineering from R.H. Gray, Manager, Shuttle's Project Office, Kennedy, July 24, 1975 (Kennedy Space Center Archive, Florida).

> stabilize where's the right position for those panels.[52]

> We had a fleet size that we weren't real sure about. So how many hangers did you need to put these orbiters in and you took a look, well if you fly 60 a year you've always one or two in orbit so you don't have to have a hanger for each vehicle because there is always one flying. When you fly seven a year you don't always have one in orbit so you got to have some place to park it. So it changes things like that. How many buildings to you have to build and how many cranes do you have to have in the assembly building. Are there enough cranes to handle two at a time or do you need to handle two at a time.[53]

> I had to lay out the criteria for the runway before the shuttle was designed because ... somehow throughout the history of the United States the Congressional people have really got to where they control the construction of facilities budget, almost down to a very fine level. So the lead time on construction of facilities budget is like five years ... So in order to get a runway built in time for what we thought we were going to need it on the programme, we had to start laying out the criteria for runway and convincing the people in Congress that yes we need this runway, before the shuttle was finalized at all.[54]

The most severe impact, however, was a reduction in the amount of instrumentation and check-out systems Kennedy wanted on the shuttle to ease maintenance and turnaround procedures.

> Providing the instrumentation cost ... money and weight; and neither one of those things could we afford.[55]

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52 John Tribe, interview with the author, July 28, 1995.

53 Samuel Beddingfield, interview with the author, July 31, 1995.

54 ***Ibid.***

55 Herb Yarbrough, interview with the author, September 5, 1995.

> Everything we wanted to do down here [Kennedy] in the way of maintenance that added weight, [went] out; and we have lived to regret this for many years.[56]

> [O]ne of the things that we were forced to restrict early on in the program, because of financial constraints, was the ... attention that was given to the turnaround and the design of the systems for self-test and things of that sort that would of improved the turnaround capability.[57]

> If they built the vehicle exactly the way we wanted it, it would be easy to checkout during turnaround, but it would be too heavy to fly any payloads. So that was a compromise. We didn't get everything we would have liked.[58]

As a consequence, the requirement of 160 hours turnaround time between landing and launch was placed in jeopardy. The turnaround time of two working weeks was specified from very beginning of the shuttle programme, when NASA was still pushing its two-stage, fully-reusable configuration.[59] And although many other aspects of the shuttle changed in the politics of post-Apollo, the turnaround time remained.

> The original criteria was to be able to turn it around in two working weeks. ... We obviously can't do that, but that was a big driver ... and they changed a lot of the other criteria about the shuttle ... but they never changed the goal

56 John Tribe, interview with the author, July 28, 1995.

57 James Jackson, interview with the author, July 12, 1995.

58 Robert Sieck, interview with the author, August 1, 1995.

59 NASA, ***Space Shuttle Requirements Document Level 1***, Office of Manned Space Flight, July 1, 1970 (NASA History Office Archive, Washington DC).

> of being able to turn it around in 160 hours; so it made planning for it very difficult.[60]

When Columbia arrived at Kennedy in March 1979, the machine struck a sense of awe into many members of the Center. Despite all the preparations and planning, Columbia was a major revelation; as Robert Sieck remembered:

> Compared to other flight hardware that we had received down here during the Gemini and Apollo program ... it wasn't anything like we had had before. The complexity of it, the size of it, the number of components and rules and the requirements that went with it, were an order of magnitude more than anybody down here had experienced; and all of the things that we had learned on the Gemini and Apollo program ... were not applicable to shuttle. It was like starting over again.[61]

And Ted Carey recalled:

> Then when the first orbiter arrived, which was 1979, we ... had to sit down to figure out how you actually did this, which turned out quite a bit different from what we thought. We had originally thought you could turn an orbiter round in two weeks but after we saw one and ... saw all the complexity we realized that was not possible. So we had to figure out how to get ready for the first flight.[62]

Within a couple of months after Columbia's arrival, Kennedy's top management started getting discrepancy reports by the hundreds. It thus became obvious very quickly, that NASA's expectations and forecasts for test

60 Samuel Beddingfield, interview with the author, July 31, 1995.

61 Robert Sieck, interview with the author, August 1, 1995.

62 Ted Carey, interview with the author, July 22, 1995.

and checkout were an order of magnitude wrong.[63] As Rockwell Engineer (Kennedy Div.) John Tribe commented, when:

> you build a vehicle of that magnitude and that complexity, then the checkout takes forever. You got to check every redundant path, every piece of wire, every component.[64]

Columbia's first flight eventually took place on April 12, 1981. The first launch was originally scheduled for April 10, but the back-up flight computer failed 20 minutes before lift-off.[65] Thus, the launch was rescheduled for two days later. This time everything went according to plan and Columbia climbed into the Sky on the Sunday morning with no problems. However, once in orbit a potentially serious problem emerged. Television monitor cameras, fitted to observe the payload bay doors open, caught sight of missing tiles on the orbital manoeuvring system, pods. This, in itself, was alarming to NASA, but what concerned mission control most was what if tiles on the bottom of the orbiter were also missing. NASA spent all of April 13 endeavouring to find a solution, but as Hans Mark recalled:

63 Ted Carey, interview with the author, July 22, 1995; Herb Yarbrough, interview with the author, September 5, 1995; Norman Chaffee, interview with the author, September 6, 1995.

64 John Tribe, interview with the author, July 28, 1995.

65 John Garman, 'The "Bug" Heard 'Round the World,' ***Software Engineering Notes*** 6 (October 1981), pp 3-10.

> There was, of course, not much that we could really do. If there were indeed tiles missing from the portion of Columbia that would experience the highest heating rates, then we would only find out by making the attempt to bring her back to earth. So we made our best calculations and estimates, but, in the final analysis we had to ... hope for the best.[66]

On April 14, Columbia returned safely. The first "actual" test had been completed.

Going Operational.

On July 4, 1982, (American Independence Day) President Ronald Reagan welcomed Columbia home from its fourth flight. From a flag-decked rostrum, Reagan announced that the shuttle was ready for its transition from development to operations. He was reading straight from a NASA policy document.[67] NASA had already decided that it was going to fly four test flights and then declare the shuttle fully-operational,[68] but:

> nobody knew what that meant, because every flight after that time was anything but operational. So that was quite arbitrary.[69]

> ... there was no way it was operational, after the first four flights. However, we began to fly scientific payloads anyway, because we knew the press would be jumping on us.[70]

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66 Hans Mark, ***Space Station*** pp 124-125.

67 Jamès Abrahamson, interview with the author, July 5, 1995; Francis Hoban, interview with the author, May 15, 1995.

68 Hans Mark, interview with the author, September 9, 1995.

69 James Abrahamson, interview with the author, July 5, 1995.

70 Hans Mark, interview with the author, September 9, 1995.

A big issue for NASA's upper management in the 1980s was transforming the culture of the agency, from one that treated every flight as unique to one that conformed to "routine operations".[71] Once the design, development test and engineering was essentially "completed" and the shuttle moved into "routine operations", the NASA penchant for invention surfaced anew. NASA's engineers wanted to begin work on the next project, which was the space station. But since the political climate was not amenable to committing funds for a space station at that time, NASA's engineers tended to find things on the shuttle that they could go and work on: as a Johnson engineer, Norman Chaffee recalled:

> As a result we started focusing on every little anomaly that would occur on a shuttle flight. [Each] would be carefully logged and given a number and it would be worked to the nth degree. Now in many flights we had, because the shuttle was still a developmental type of vehicle, there was enough things that were routinely going amiss, so there was plenty of things to work on, but it would get almost humorous, because when missions went well and there were no anomalies the managers would invent anomalies, things that they normally weren't interested in knowing about or didn't care about. For instance, on the Auxiliary Power Unit we had an exhaust duct temperature [gauge] that failed every flight. ... It was a bad design you didn't need the data. We'd fix it or let it go, but the next time you fly it, it would break again, nobody really cared much. I remember one flight, everything was working perfectly but this temperature measurement, and the Program Manager decided he wanted a crash investigation of why this thing has failed because that was the only thing that had gone wrong, so we must need to work on that. I think NASA is a problem solving organization

71 James Beggs, interview with the author, June 6, 1995; James Abrahamson, interview with the author, July 5, 1995.

> ... and if NASA doesn't have a real problem to work on NASA will make up a problem to work on, and that just part of the culture.[72]

Rockwell engineer, Ted Carey, however, held a different perspective on that period.

> The change traffic was generated by the hardware feeding back to the designers what was wrong with it. We had a very large number of discrepancy reports, we call them PR's (problem reports), ... and there was a very conscience desire to not only repair a problem, but to eliminate its cause. ... So for the first five or six flights, as a matter of fact on into the ... thirtieth flight, there was still a very high percentage of work being done as a result of discrepancies being recorded on the ground. We had extensive test and checkout of the ground. We actually did a basic re-check of everything every flight. ... The hardware is talking to you, you have to listen to it ... most of the problems that you have in the space business try to tell you that they are there ... so a lot of those resulted in design changes. ... As a matter of fact, at one point [NASA Administrator, James] Beggs decided that he was going to cut back the cost of the design engineering people at Downey, so that he would stop the engineering changes from coming in. Most of us thought that was very unintelligent. Those engineering changes were not cosmetic and they were not insignificant and to hide your head in the sand and pretend that those changes were not necessary might seem like seem like a good management technique, but it's not.[73]

Nevertheless, for NASA Administrator, James Beggs, and Johnson's Director, Christopher Kraft, the continuous changes in design were seen as a major hinderance in the transition to an operational mode.

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72 Norman Chaffee, interview with the author, September 6, 1995.

73 Ted Carey, interview with the author, July 22, 1995.

> There were several problems: one is that unfortunately engineers, being engineers, like to make thing better as time goes on. [And] because engineers like to improve it, they keep adding bells and whistles to the machine and you would like them not to do that, but unfortunately both engineers and astronauts like the latest equipment. ... So the tendency is to want to put the latest of everything in the machine and you have to fight that a little bit, but you have to give in as well.[74]

> Engineers are notorious for the cliche that the better is the evil of the good, and so they continually try to make it better. ... [As such] NASA has maintained an R&D mode as opposed to an operating mode. ... You can't continue to play with it if your going to drive the operating costs down.[75]

The continuous modifications and changes to the design raised a further problem in the transition to routine operations: none of the orbiters were the same. Standardization is an important part of operational technologies, especially complex technologies. Without commonality, the procedures and logistics of service and repair become more complicated. NASA was faced with orbiters rolling off the production line that were all subtly different. As James Beggs recalled, this presented a major problem in the drive towards efficient operations:

> Everything NASA builds is a unique article ... so there is a difficulty inherent within the business in standardizing the equipment. We ... have looked from time to time at making a common bus which would be something you could produce in quantity and then put the unique instruments and flight equipment aboard the bus, but even that's difficult. ... I think we're stuck with the fact

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74 James Beggs, interview with the author, June 6, 1995.

75 Christopher Kraft, interview with the author, September 1, 1995.

> that these programs will be non-standard. Everything changes ... as we learn more about them. ... Each of the orbiters was different to the one before and that presents problems. As you go along you try to improve the flight characteristics and the structural capability of the machine and so the heaviest and least efficient machine is the first one; that's Columbia. ... That means that getting spare parts, and what have you, is difficult because some parts don't fit and they had to be kept specially.[76]

The problem of spare parts, however, was not only due to non-standardization. NASA faced a spare part shortage in the early 1980s, mainly because of a lack of logistics planning and an inadequate inventory of replacement parts due to the tight budget environment. For example in 1984, NASA only one spare engine that had to be shared by all the orbiters. Cannibalization of parts from one orbiter to the next was thus a common occurrence during the early operational years.

> One of the decisions that had to be made, in order to live within the budget, ... we couldn't buy spare parts. So we ended up robbing out of one orbiter and putting parts in another one and when it would come back, taking them out of that one and putting them in another one. That caused a lot of frustration that operational organizations normally don't have to live with.[77]

In 1983, Congress approved a higher budget for the procurement of spares, but the long lead time involved in

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76 James Beggs, interview with the author, June 6, 1995.

77 Herb Yarbrough, interview with the author, September 5, 1995.

their fabrication meant that shortages continued through to 1986.[78]

Shortly after Columbia was delivered to Kennedy, the new Office of Space Transportation Systems had attempted to lay down a concrete traffic model (see table 8:1 for 1979 traffic model). Before this time traffic model predictions had become confused, since different sections of NASA and the contractors had been using assorted traffic models during budgetary planning presentations.[79] However, in the wake of Columbia, NASA's flight manifest just kept on falling,[80] as the Director of Space Transportation Systems Operations, Chester Lee, recalled:

> Over the years ... the flight numbers went from 60 to 50 per year, to 40 per year, to 30, 24 per year ... then we talked 12. Now we are down to 8.[81]

The falling flight rate, of course, had a severe impact on the cost-per-flight; an issue that had been politically sensitive since the shuttle's conception.

In 1976, Deputy Administrator, George Low had established a pricing policy, which averaged the shuttle's cost-per-flight at around $18 million in 1975 dollars (see

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78 Letter from James Fletcher to Edwin Garn, Chairman on HUD Independent Agencis Committee on Appropriations, July 8, 1983 (NASA History Office Archive, Washington DC); Letter from James Fletcher to David Stockman, Director of OMB, April 12, 1982 (NASA History Office Archive, Washington DC); Letter from James Fletcher to Bill Nelson, Chairman on Space Science and Applications Committee, June 20, 1985 (NASA History Office Archive, Washington DC).

79 Letter from Chester Lee to John Yardley, March 30, 1979 (NASA History Office Archive, Washington DC).

80 'NASA Schedules 34 Shuttle Flights Through '85' ***Defense Business Daily*** (June 3, 1981) p 184.

81 Chester Lee, interview with the author, May 2, 1995.

Table 9:2.

Shuttle Prices.

User Category.	Phase I.[a]	Phase II.[b]
Non-US Government.	\$19.7 - 22.2 M	\$19.3 - 21.2 M
Civil US Government, Canada and ESA.	\$17.1 - 19.3 M	\$16.2 - 18.1 M
DOD.	\$12.3 - 14.0 M	\$11.7 - 13.2 M

a. Phase I represents the first three fiscal years of shuttle operations.
b. Phase II represents the nine fiscal years subsequent to Phase I.

Source: Memorandum from George Low to James Fletcher, May 28, 1976 (NASA History Office Archive, Washington DC).

table 8:2).[82] By 1984, The Associate Administrator for the Office of Space Flight, Jesse Moore, indicated that the total average cost of operating the shuttle has grown to an average of $60 million per flight (in 1975 dollars).[83] NASA blamed the reduced flight activity, but there was a recognition that the projected costs were overly optimistic even for the high flight rates assumed. In 1981, NASA's Acting Administrator, Alan Lovelace, had commented that the shuttle's operations costs would not meet the projected figures drawn up in the 1970s. Those estimates he remarked:

> were partially designed to defend a program on the basis of its cost effectiveness [and] I happen to not agree with those figures.[84]

Nor did the General Accounting Office.

In 1982, just before the completion of Columbia's forth test flight, the General Accounting Office released a report claiming that the shuttle could cost $116 million per flight (in 1975 dollars).[85] As such, argued the General Accounting Office, NASA would effectively be subsidizing non-government users.

> It is ironic that at a time when NASA's programs are suffering due to budget constraints, they are

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82 Memorandum from George Low to James Fletcher, May 28, 1976 (NASA History Office Archive, Washington DC).

83 ***Review of Space Shuttle Requirements, Operations, and Future Plans***, Report prepared by the Subcommittee on Space Science and Applications, US House of Representatives (Washington DC, US Government Printing Office, 1984).

84 Alan Lovelace, quoted in, 'Lovelace sees Fewer Flights, Increased Costs Likely For Shuttle' ***Aerospace Daily*** (May 6, 1981), pp 25-26.

85 GAO, ***NASA Must Reconsider Operations Pricing Policy to Compensate for Cost Growth on the Space Transportation System*** Report to the Congress, February 23, 1982 (General Accounting Office Distribution Center, Washington DC), p 14.

Table 9:1.

1979 Space Shuttle Traffic Model.

Year.	81	82	83	84	85	86	87	88	89	90	91	92	Total
KSC.	7	16	18	25	30	36	34	40	38	41	38	30	353
VAFB.	0	0	2	6	12	15	18	18	15	16	17	15	134
Total.	7	16	20	31	42	51	52	58	53	57	55	45	487

Source: Letter from Chester Lee to John Yardley, March 30, 1979 (NASA History Office Archive, Washington DC).

> locked into a pricing policy that encourages [shuttle] use at NASA's expense and at the expense of its space science, applications and aeronautics programs.[86]

The idea that NASA would be subsidizing non-government users caused a stir in Congress. Thus, a debate emerged over whether NASA should charge users marginal costs or total average costs. Many members of Congress were incensed by the idea of government subsidizing commercial users and pushed for a policy whereby non-government users would pay a share of the fixed costs.[87] NASA, however, argued that commercial users would pay all costs, because government has to pay for the fixed costs regardless, so marginal costs, which would be all the expenses of a particular flight, could not constitute a subsidy.

Capturing the commercial market was of utmost importance to NASA. For the shuttle to be "effective" NASA needed to monopolize the space market; government, military and commercial. Winning the debate on marginal costs was crucial if NASA's vision of rapid expansion in space was to be fulfilled. NASA Administrator, James Beggs, made this point in his testimony to Congress:

> The [marginal] costs recovery policy ... would allow for an internationally competitive price and also permit the industrial entrepreneurs to develop or improve technology products with some

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86 *Ibid,* p 19.

87 ***Space Shuttle Operations***, Hearings before the Subcommittee on Science, Technology, and Space, US Senate (Washington DC, US Government Printing Office, 1982); ***Space Shuttle Requirements, Operations, and Future Plans***, Hearings before the Subcommittee on Space Science and Applications, US House of Representative (Washington DC, US Government Printing Office, 1984); ***Review of Space Shuttle Requirements, Operations, and Future Plans***, US House of Representatives.

> extensive, but not excessive risk of capital. ... Total cost recovery ... may not be non-competitive for the current spacecraft and satellite customers and might result to be too expensive to encourage the developers of new space products.[88]

And indeed, Beggs was right. The commercial community was primarily interested in cost-per-flight. A NASA Advisory Council study had found that many commercial users would be willing to use the shuttle, but only if it was competitive with expendable launch vehicles.[89]

However, this was not the only apprehension expressed by potential commercial users. Their overall concern was that NASA was too preoccupied with developing the shuttle, rather than improving its customer service. Indeed, the commercial world:

> perceive too much fascination by NASA with the role of the astronaut, with in-orbit checkout, and with recovery, and not enough emphasis on simply transporting payloads to orbit on schedule at the lowest cost and maximum dependability.[90]

Delays and schedule problems had instilled a lack of confidence in the shuttle on the part of the commercial world. In addition, the interface requirements and the amount of documentation required by NASA for the shuttle, vastly exceeded what commercial users had become accustomed

88 James Beggs, quoted in, ***Review of Space Shuttle Requirements, Operations, and Future Plans***, p 33.

89 NASA Advisory Council study of effective shuttle utilization, conducted by a NAC Task Force, 1983 (NASA History Office Archive, Washington DC); Letter from Daniel Fink, Chairman NASA Advisory Council, to James Beggs, November 17, 1983 (NASA History Office Archive, Washington DC).

90 ***Ibid,*** p 10.

to with expendable launch vehicles; as NASA's Associate Administrator for Science and Applications, Burton Edelson, recalled:

> My first involvement, while I was still at COMSAT corporation, was to try to determine if the shuttle would be effective in launching communication satellites and they were advertising a low price. Despite that, INTELSTAT never decided to use the shuttle ... in every case they used either the Atlas-Centaur or the Arian vehicles, which were the spacecraft flying at that time. And the reason was that both the Atlas launches and the Arian launches were configured to the spacecraft, whereas the shuttle demanded that you re-engineer and rebuild your spacecraft to be satisfactory to launch on the shuttle; and primarily to keep the shuttle safe from any danger form the payload. Well that is just not a viable way to develop a launch vehicle. The US then required that all commercial launches would go on the shuttle ... but of course INTELSTAT did not come under the authority of the United States and they could choose any vehicle they wanted and so they chose [expendables]. So it was clear ... that the space shuttle would never be good for launching commercial payloads; communication satellites. Even if the price was competitive, the reliability and dependability were so low that it couldn't be used for commercial communication satellites. ... It's true that the shuttle launch environment was benign, it didn't subject the payload to the G's [force of gravity], on acceleration that a rocket launch would have. On the other hand, you needed lots of protective devises to protect the shuttle and the health and safety of the shuttle crew, which you normally don't worry about. Also, it provided much less access to the payload, so it made it much harder to design and build a satellite to launch on the shuttle, because one thing is you had to [have it configured] a year ahead of time and it had to go through all kinds of checks ... and you had no control over it then. You couldn't make any changes. ... Whereas with an expendable launch vehicle, the launch vehicle accommodates the payload. ... If the payload operator wants to change something three days before the launch,

> well then he just changes it three days before the launch.[91]

During 1983 and 1984 the shuttle's flight rate climb slowly, reaching a peak of 9 in 1985. The agency was still on a very steep learning curve, but as Herb Yarbrough recalled, NASA was optimistic about increasing its flight rate further.

> When the folks over in the mission operations directorate came to talk to the program office, Glen Lunney [Shuttle Programme Manager] asked them, hey we got 18 flights on the books for next year can we do that? And they'd say sure, we had 18 this year. He said no we didn't we only flew 9 and they said yeah but you guys changed your mind on every flight at least once so we had to every damn one of them over again.[92]

But on January 28, 1986 Challenger exploded 73 seconds into its flight. All the crew lost their lives. The event marked a turning point for NASA and as Alex Roland has suggested the end of the romantic era of spaceflight.[93]

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91 Burton Edelson, interview with the author, June 22, 1995.

92 Herb Yarbrough, interview with the author, September 5, 1995.

93 Alex Roland, 'Barnstorming in Space: The Rise and Fall of the Romantic Era of Spaceflight, 1957-1986,' Radford Byerly, (ed) ***Space Policy Reconsidered*** (San Francisco, Westview Press, 1989).

Chapter 10

Potentialities and Imperatives: The Shapers and Forces of a Technology

> Technological development has come to be viewed as an autonomous thing, beyond politics and society, with a destiny of its own which must become our destiny too. From the perspective of here and now, technological development has become simply the blind weight of the past on the one hand and the perpetual promise of the future on the other.[1]

For a variety of contemplations about the future, the technologies associated with space have personified human progress. Through the mediums of science fiction, "popular science", journalism and academic thought, the "belief" in the beneficial nature of science and technology have been assimilated with US axioms of the "frontier spirit" and the "American Dream" to make humanity's quest to reach the stars appear foreordained.[2] As the protagonists vied to construct their machine, they continually evoked and reinforced this complicated nexus of ideas about space travel and the *fortunes* of human history. The space industry's leading prophets meticulously carved an image of

1 David Noble, ***Progress Without People: New Technology, Unemployment, and the Message of Resistance*** (Toronto, Between the Lines, 1995), pp 5-6.

2 For a comprehensive analysis see, Dale Carter, ***The Final Frontier: The Rise and Fall of the American Rocket State*** (London, New York, Verso, 1988).

the shuttle as the precipitator of a revolution akin to those thought to be engendered by the ship, train and aeroplane that preceded it. The shuttle symbolized the maturation of the "space age". Routine space travel meant an "exploitable" environment. With space no longer the restricted terrain of specialists, new industries and new communities would be forged high above the Earth's surface by the inventors and entrepreneurs of tomorrow.[3] It was a vision that was bright and technically led; a progeny of an era of technological enthusiasm, when human progress was firmly tethered to advancements in science and technology.[4]

> ... the dominant ideology of progress took it for granted that the growing domination of nature by man was the very measure of humanity's advance.[5]

Indeed, those that stood in opposition to the shuttle were often caricatured as standing against progress itself and denounced as heretics, utopians or reactionaries.[6]

The economic surge of the 'golden years' of the 1950s and 1960s seemed powered by technological revolutions.[7] Hence, government policies towards technological change

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3 See chapter 2, ft's 6, 10; chapter 3, ft's 32, 37, 38, 103, 105; chapter 6, ft's 12, 80, 87, 88, 91; chapter 8 ft's 14, 30, 50; chapter 9, ft's 3, 4, 6, 13-15.

4 Thomas Hughes, ***American Genesis: A Century of Invention and Technological Enthusiasm 1870-1970*** (New York, Viking Penguin, 1989); Jan Golinski, ***Making Natural Knowledge: Constructivism and The History of Science*** (Cambridge, Cambridge University Press, 1998).

5 Eric Hobsbawn, ***The Age of Extremes*** p 261.

6 See chapter 2, ft, 37 chapter 3, ft, 114; chapter 6, ft, 11.

7 Eric Hobsbawn, ***The Age of Extremes*** chapter 9.

sought to encourage invention and innovation on the assumption that they would ultimately improve standards of living. In the two decades following the Second World War, the US government's contribution to research and development grew significantly. The shuttle was a product of this period; part of a theorem that suggested the role of government and state was to correct the follies of the market and promote economic growth through scientific advancement and technological innovation. These undertakings usually followed a Keynesian macro-economic abstraction which dictated that government should avoid direct competition with private capital. Keynes's pyramids and cathedrals of the twentieth century came in the form of "high-technology:" that is technological enterprises thought to be too high risk for the market.[8] Such technological endeavours, so the theorem maintained, could only be beneficial: they would promote employment, skills and expand the industrial infrastructure. For the champions of the shuttle, these "spin-offs" from the accumulation of new knowledge and new technology, were well rehearsed

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8 Phyllis Deane, ***The State and the Economic System: An Introduction to the History of Political Economy*** (Oxford, Oxford University Press, 1989); Christopher Freeman, Carlota Perez, 'Structural Crises of Adjustment, Business Cycles and Investment Behaviour,' Giovanni Dosi, Christopher Freeman, Richard Nelson, Gerald Silverberg, Luc Soete, (ed) ***Technical Change and Economic Theory*** (London, New York, Pinter Publishers, 1988), pp 38-66; Richard Nelson, 'Institutions Supporting Technical Change in the United States,' Giovanni Dosi, Christopher Freeman, Richard Nelson, Gerald Silverberg, Luc Soete, (ed) ***Technical Change and Economic Theory*** pp 312-329; Malcolm Goggin, (ed) ***Governing Science and Technology in a Democracy*** (Knoxville, The University of Tennessee press, 1986); Richard Nelson, Richard Langlois, 'Industrial Innovation Policy: Lessons from American History,' ***Science*** 219 (February 18, 1983), pp 814-818; Roy Rothwell, Walter Zegveld, ***Innovation and the Small and Medium Sized Firm: Their Role in Employment and in Economic Change*** (London, Frances Pinter Publishers, 1982); Colin Norman, ***The God that Limps: Science and Technology in the Eighties*** (New York, W.W. Norton & Co, 1981).

compositions of promotional rhetoric used to support large public investments into NASA's human space programme.[9]

Within the dominant ideology of progress, building the shuttle was seen as a "logical" undertaking that would inevitably lead to the progressive "conquest" of space.[10] Yet, although instrumental to the realization of NASA's shuttle, the circumstances that underlaid the machine's reason for being were far more complicated. To understand the development of the shuttle as merely a manifestation of the drive for progress, is to ignore a history rich in complexity. Its materialization relied on the mobilization and juxtaposition of numerous heterogeneous elements from both the material and social worlds.

The starting point of this historiography was the exposure of *choice.*[11] Scattered throughout the tangled fabric of the shuttle's history were *alternatives*; different paths of development, various points of intervention and the ever present possibility of retrenchment. As the end result of over ten years of research, design, development and fabrication, the "inventing" of NASA's shuttle was a complicated process, which involved a complex array of interactions and ranges

9 Chapter 6, ft 90.

10 See chapter 2, ft 6, table 2:1. Developments in space technology are still couched in the rhetorical argumentation of progress today. See for example, Leonard David, 'To Boldly Go For Profit,' ***Scotland on Sunday*** (March 30, 1997).

11 Marcel LaFollette, Jeffrey Stine, 'Contemplating Choice: Historical Perspectives on Innovation and Application of Technology,' Marcel LaFollette, Jeffrey Stine, (ed) ***Technology and Choice: Readings from Technology and Culture*** (Chicago, The University of Chicago Press, 1991), introduction.

of choice. Once NASA set the process of technological change in motion, it took on many directions and contained a multitude of potentialities. The design that eventually dominated (whether it was the shuttle's overall configuration, a sub-system, or just part of a sub-system) represented a *particular* solution rather than the only one.[12] Behind the form, function and purpose of each technology was a set of decisions about which path to take. For every avenue taken there were many others that were ignored or rejected; for every problem that arose, several solutions existed simultaneously; and for each solution employed, came a whole new set of problems. Choosing between a variety of alternative options was thus a pervasive part of design and development practice. From the shuttle's inception through to it operation, different technological potentialities were available and in the process of winnowing each one out, other alternatives came to light.

The sheer number of choices were at their most prevalent during the design phase. The shuttle designs emanating from both the contractors and from areas of NASA came in all shapes and sizes.[13] Indeed, there were even those, both within and outside of NASA, who thought it

12 John Law, Michel Callon, 'The Life and Death of an Aircraft: A Network Analysis of Technical Change,' Wiede Bijker, John Law, (ed) ***Shaping Technology/Building Society: Studies in Sociotechnical Change*** pp 21-52; Thomas Hughes, ***American Genesis***.

13 See chapter 2, ft 13 and tables 2:2, 2:3, 2:4.

unnecessary to develop a reusable vehicle at all and advocated modifications to the existing expendable systems.[14] This range of potentialities was not just confined to matters of scale. In matters of detail choices between differing paths of development were also typical.[15] It would be wrong to assume, however, that once a design becomes established choice is ultimately surrendered. Surface impressions of the shuttle design presented in 1973 and Columbia, completed in 1981, may not reveal much deviation.[16] Nevertheless, throughout the "development years" a whole new set of choices arose as the various problems of fabrication came to light. The shuttle programme entered into a period of *fragile stabilization* after the design phase, where though there was a powerful tendency to shift away from heterogeneity towards universality, stabilization, alignment and control, deviation remained a significant part of the underlying process.[17]

By emphasising the existence of choice in technological change it then becomes possible to understand its social dimension. The decision making process was not governed solely by the *constitution* of technology. The

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14 See chapter 2, ft 10

15 See chapter 4.

16 See figure 4:1 and print 9:1.

17 See chapter 7.

outcome of a shuttle design, the process of turning that design into a technological system and the method of operating that system, depended on more than just the application of technique. As Thomas Hughes has noted, technological change only appears as "natural" or "logical" because large technological systems have embedded within them the characteristics of the past. Such massive systems have an inertia of motion analogous to that of the physical world. Their mass of technical and organizational components tend to maintain their steady growth and direction.[18] Donald MacKenzie and Steven Yearley have also highlighted that patterns of technological change become institutionalized, thus their internal dynamics are often veiled from "public" view.[19] Once the "black box" of technology is opened, however, its intricate and paradoxical nature is revealed.

The chief protagonist in the shuttle's history was, of course, NASA. It was the organization that fostered the mammoth activity to transform knowledge into materiality. But NASA cannot, in the conventional sense, be seen as the "inventor" of the shuttle. The shuttle, far from the

18 Thomas Hughes, ***American Genesis*** p 460.

19 Donald MacKenzie, ***Inventing Accuracy***, pp 385-387; Donald MacKenzie, ***Micro Versus Macro Sociologies Of Science and Technology*** (Edinburgh, PICT Working Paper No. 2, 1988); Donald MacKenzie, ***Economic and Sociological Explanations of Technological Change*** (Edinburgh, PICT Working Paper No. 27, 1990); Donald MacKenzie, ***Theories of Technology and the Abolition of Nuclear Weapons*** (Edinburgh, Working Paper in Sociology, 1995); Steven Yearley, ***Science Technology and Social Change*** (London, Unwin Hyman Ltd, 1988).

product of a lone inventor, or pure application of science,[20] was brought into existence through the combined labours of tens of thousands of people and the fusion of millions of separate parts. Decisions were thus scattered across a wide social spectrum. The shuttle's "successful" translation into a working machine largely depended, therefore, on what John Law has termed 'heterogeneous engineering'.[21] NASA had to establish a shape for the shuttle that would allow it to survive. This meant that along with the material, it had to "engineer" social, political and economic matters. Rather than an autonomous thing, the shuttle formed part of a "seamless web" between science, technology and society: it could not exist without the social interactions within and among social groups.[22] Social matters were, therefore, as a significant influence on the content of the shuttle as technological or scientific matters.

As the invention of NASA's shuttle was a collective process, no one individual had complete control over its

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20 Indeed, this can be said of other technologies. See, Donald MacKenzie, ***Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*** (Cambridge Massachusetts, The MIT Press, 1993), especially chapter 2.

21 John Law, 'Technology and Heterogeneous Engineering: The Case of the Portuguese Expansion,' Wiebe Bijker, Thomas Hughes, (ed) ***The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*** pp 111-134; John Law, 'The Anatomy of a Socio-technical Struggle: The Design of the TSR2,' Brian Elliott, (ed) ***Technology and Social Process*** pp 45-69; John Law, Michel Callon, 'The Life and Death of an Aircraft: A Network Analysis of Technical Change,' Wiebe Bijker, John Law, (ed) ***Shaping Technology/Building Society: Studies in Sociotechnical Change*** pp 21-52.

22 Thomas Hughes, 'The Seamless Web: Technology, Science, et cetera, et cetera,' Brian Elliott, (ed) ***Technology and Social Process*** pp 9-19; Wiebe Bijker, 'The Social Construction of Fluorescent Lighting, or How an Artifact was Invented in its Diffusion Stage,' Wiebe Bijker, John Law, (ed) ***Shaping Technology/Building Society*** pp 74-102; Donald MacKenzie, ***Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance***; Trevor Pinch, 'The Social Construction of Technology: A Review,' Robert Fox, (ed) ***Technological Change*** pp 17-35.

composition, function or purpose. Buried deep with the technology can thus be found the various "interests" of those involved in its realization.[23] Interests and goals are associated with all aspects of technological change. Together they operate as contributory causes of action, which create technologies. This is not to say that interests and goals are sufficient causes of action in themselves, only that an explanation of action would be incomplete without some reference to them. They form part of the social motives of technological production.[24] Activity is, itself, modulated by interests, which lie between actors and their goals.

In part, the origin of the shuttle can be located in the expansionist interests of NASA. In a changing environment, organizations tend to monopolize existing capabilities and attempt to procure greater resources through the adoption of new goals or extending old ones. Extending the objectives of the organization serves the interests of its members, because it enables them to carry out more tasks, gain greater influence and, therefore, become indispensable within their fields of operation.[25]

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23 Trevor Pinch, 'The Social Construction of Technology: A Review,' Robert Fox, (ed) ***Technological Change*** pp 17-35.

24 Barry Barnes. ***Interests and the Growth of Knowledge*** (London, Routledge & Kegan Paul, 1977); Barry Barnes, David Bloor, John Henry, ***Scientific Knowledge: A Sociological Analysis*** (London, The Athlone Press, 1996), pp 120-129.

25 Theo Farrell, ***Weapons Without a Cause: The Politics of Weapons Acquisition in the United States*** (London, MacMillan Press Ltd, 1997), chapter 3; Peter Blau, ***The Dynamics of Bureaucracy: A Study of Interpersonal Relations in Two Government Agencies*** (Chicago, University of Chicago Press, Revised Edition, 1963), chapter 12; David Sills, 'The Succession of Goals,' Amitai Etzioni, (ed) ***A Sociological Reader on Complex Organizations*** (London, Holt, Rinehart & Winston Inc., Second Edition, 1970), pp 175-187.

The materialization of NASA's shuttle in 1968 coincided with the realization of Apollo. The old sociotechnical order, built up around Apollo, was slowly being dismantled. The grand assemblage of scientists, engineers, bureaucrats and industrial might, required a new goal if their interests were to continue to be served; and those interests were firmly centred on the development of advanced technology. Incrementalism would not suffice and was resisted.[26]

In the minds of the public, the White House and Congress, there was little differentiation between the Lunar mission and NASA. NASA had become Apollo. Ergo, the agency's orientation towards *leap-frog* innovation rather than incremental innovation stemmed, in part, from an internal perception of where the agency was going. NASA had entered the new world of post-Apollo with no concrete identity. A new approach to space operations, one that would substantially reduce the costs and risks of getting to and from space would, in the eyes of NASA's elite, bolster the organization's future. Thus, the idea of a reusable launch vehicle took shape as the key to making space a place of routine; and the goal of establishing a technological trajectory towards total reusability became the primary intention of the shuttle's designers.

[26] See chapter 2, fts 2-10, 47-50.

In the dawn light of the 1970s, however, NASA witnessed a pivotal shift in the locus of control over its activities. During the 1960s, control was essentially internal. NASA's reputation as the most thoroughly professional organization in the federal government had, to a large extent, been built upon the idealization that "political" decisions and "technical" judgements were separate. This dichotomy flourished because the agency was allowed a large amount of technical discretion against a background of relatively minimal political interference. The objective, getting to the Moon before the Soviet Union, was so important politically, that the method was essentially left in the hands of the experts. With the space race won, however, political considerations began to supersede engineering judgements. After 1969, NASA was no longer the expert, dictating the direction of space technology to a lay audience on Capitol Hill. Instead, members of the agency had to be more aware of, and become more responsive to, key actors in the political system.[27]

When individuals, groups and organizations work together then agreement is required on the things that need to be done. As agreements tend to rest on negotiation and renegotiation, this process forms a strong undercurrent

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[27] Barbara Romzek, Melvin Dubnick, 'Accountability in the Public Sector: Lessons from the Challenger Tragedy,' ***Public Administration Review*** (May/June, 1987), pp 227-238; Howard McCurdy, ***Inside NASA*** chapter 3.

influencing the direction of technological change.[28] In the process of making the concepts real, the ideas and the artifacts were not only transmitted from one actor to the next, they were collectively *composed* by the actors.[29] The design and purpose of NASA's shuttle, as a whole and in its parts, was modified as one group negotiated with another. Each interest group involved in the shuttle's history play determining roles in shaping the technology's final form.

Although shielded from the follies of the market, NASA did not operate within a vacuum. The work of the shuttle's protagonists was interwoven with the existing power relations of US society. Those who wielded social, economic and political power defined, to a considerable extent, what was and what was not technically possible. Thus, there was a limit to the transformative capabilities of NASA's heterogeneous engineers. NASA was but one of many branches in an immense state bureaucracy, all of which were involved in struggles for finite funds on Capitol Hill. Government budgets represent the outcome of political negotiations over the setting of priorities for action. Those that are successful in procuring resources are those that have

28 Anselm Strauss, ***Negotiations: Varieties, Contexts, Processes, and Social Order*** (San Francisco, Jossey-Bass Publishers, 1978).

29 Bruno Latour, ***Science in Action: How to Follow Scientists and Engineers Through Society*** (Milton Keynes, Open University Press, 1987), p 104.

prevailed in the political struggle.[30] Consequently, political expediency formed an important social imperative, required to secure and continually serve the shuttle's avaricious demand for resources, as well as to ensure the preservation of the sociotechnical order. NASA's relations with both the White House and Congress were integral to the shuttle's beginning and an important factor in its survival. Governmental influence, however, only formed one part of a much more complex power structure. Other branches of the US state and powerful sections of private capital also played determining roles in the shuttle's creation and continuation.[31] Thus, NASA had to form a wide political consensus on the direction and purpose of the civilian space programme.

In the formation of a consensus on space policy, NASA made three distinct, but related shifts in its position. First, the shuttle was decoupled from the space station; second, NASA sought political coalitions with groups that were previously hostile, or ignored; and third, NASA abandoned its penchant for total reusability. As a myriad of people and organizations were introduced into the sociotechnical assemblage, both the technology and NASA's goals underwent a process of redefinition.

30 David Noble, ***America By Design: Science, Technology and the Rise of Corporate Capitalism*** (New York, Alfred Knopf, 1977); David Noble, ***Forces of Production: A Social History of Industrial Automation*** (New York, Alfred Knopf, 1984); Paul Baran, ***The Political Economy of Growth*** (New York, Modern Reader Paperbacks, 1968); John Kenneth Galbraith, ***The New Industrial State***; Jeffrey Pfeffer, ***Power in Organizations*** (Boston, Pitman Publishing, 1981).

31 See chapter 2, fts 19-31, 37-75; chapter 3, fts 84-116; chapter 6; chapter 8.

Between 1968 and 1970, the shuttle was subordinate to a space station, pictured only as a means to a greater ends. By the end of 1971, the shuttle was extolled as a pragmatic, universal and economical technology in its own right; and by the end of 1972 exhorters for the shuttle had described it as indispensable to the needs of national security and economic advancement. Two processes can be seen at work here: what Bruno Latour has called a 'translation of interests;'[32] and what Langdon Winner has termed, 'reverse adaptation.'[33] Once the shuttle was separated from the space station, its utility was tailored to cater for the interests of others.[34] The two claims that emerged most forcibly during 1971, were the shuttle's ability to provide routine and economic transportation to space. These utilities were promoted in an endeavour to gain allegiance with the military, the scientific community and the commercial world. Thus, the new consensus was founded on the exploitation, as opposed to the exploration, of space. Without the space station, NASA had to "seek missions" for the shuttle that would match its technical capabilities. So the retrieval, repair and service of satellites in orbit also became the mainstay of the

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32 Bruno Latour, ***Science in Action*** chapter 3.

33 Langdon Winner, ***Autonomous Technology: Technics-out-of-Control as a Theme in Political Thought*** (Cambridge, Massachusetts, MIT Press, 1978), pp 238-251.

34 See chapter 3, fts 29-42.

shuttle's advancement; regardless of whether anyone really wanted such a capability.

NASA's traditional support from its industrial allies was, of course strong. A recession within the aerospace industry at the end of the 1960s meant that firms like Rockwell, McDonnell Douglas, General Electric and Grumman Aerospace, were eager to secure new government contracts for large scale technological programmes. These allegiance were critical politically when Nixon was fighting his second election in 1972.[35] Nixon's political advisors recommended approval of the shuttle on the grounds that it would provide employment directly in the skilled areas of science and technology and in other non-skilled sectors via the sub-contracting out of production. Indirect employment would also benefit through the maintenance of local economies in those areas that development and production took place. Thus, NASA also employed what Latour has termed the 'invisible detour'.[36] Through a reinterpretation of the shuttle as necessary to economic growth and scientific advancement, NASA gained the advantage of translating a particular interest into a much larger one: the "interests of the nation". Any threat to the former became a threat to the latter.[37]

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35 See chapter 6, fts 2-20.

36 Bruno Latour, ***Science in Action***.

37 For a good example of this see chapter 6, fts 21-44.

The kernel of many of these transformations can, however, be located long before the space station was shelved, in the subtle differences between the frames of references of the Office of Manned Space Flight and the other shapers of space policy. The Office of Manned Space Flight was predominately interested in creating technological capabilities, whereas all the other groups focused their attention on establishing mission objectives.[38] The shuttle had originated from the former, rather than the latter. With no specific mission to tailor the technology to, justifications for the shuttle could be constructed around a variety of rationales that would convince other groups that its development would be in their advantage. The means were transformed into the ends. Rather than a method to achieve a particular goal, new capabilities and the possibility of economic and routine access to space, were turned into objectives in themselves.

The purpose of the technology was, therefore, shaped through the negotiations of different interest groups. Its function, a manifestation of the convergence of those interests. As the goals of the technology changed, so did its requirements and, thus, its specifications and configuration. The very content of the shuttle was shaped by negotiation. This was effectively demonstrated in NASA's "allegiance" with the US Air Force. Once the goals of the

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[38] See chapter 2, fts 48-49.

shuttle changed, NASA needed Air Force support to bolster it position. For its patronage, the Air Force demanded certain key requirements: specific, crossrange capability, lifting capability and payload bay capacity. All were incorporated and each altered wing shape, engine thrust and orbiter size.[39] In tandem with the Air Force, certain parts of the White House bureaucracy also had a significant impact on the shuttle's form. The key impediment to NASA's plans was development costs. Scepticism within the political arena over NASA's requests for a multi-billion dollar investment in new space technology was evident. The Office of Management and Budget, the Office of Science and Technology and the President's Science Advisory Committee, all demonstrated and acted upon their apprehensions over the costs associated with the agency's proposals. Misgivings were not just centred within the White House. Vocal opponents within Congress also attempted to focus an anti-shuttle campaign and mobilized enough opposition to halt the programme. Activation of a project on the size and scale that NASA envisaged was, therefore, interrupted by a political will to stem public spending and to check NASA's intangible justifications for a $20 billion investment in new technology. The result was a radical change in the configuration of NASA's shuttle from its original two stage

39 See chapter 3, fts 56-65.

design to an orbiter incorporating an expendable fuel tank and two solid fuelled rocket boosters.[40]

Negotiation was, therefore, a fundamental part of the shaping process: necessary to maintain confidence in, and secure funding for, the project. Opposition to the shuttle programme existed at the highest levels of government. Without the defence of other vital power allies, NASA could not have put in place the foundations of the sociotechnical order and from these foundations construct the gargantuan assemblage that formed the shuttle. The convergence of NASA's own organizational interests with the interests of other parties thus helped shape both the shuttle's composition and its utility.

It would be a mistake to presume, however, that interests and negotiation were only involved in matters of scale and that decisions on matters of detail were based on technical criteria alone. NASA was not itself a homogeneous entity and individuals and groups within the organization, sought to locate themselves in positions that would render them indispensable to the system. Large organizations, like NASA, can be seen as a conglomeration of "political communities" each with their own culture and distinct ways of thinking about the way the organization's missions should be conducted. Thus, each community will not only have a notion of its own role, but will also form notions

40 See chapter 3, fts 69-82.

about the roles of other communities within the organization. The essence of an organization, and the technology it produces, can then be defined and redefined through the ideological and political struggles that occur within the organization amongst its own members.[41]

At the start of the shuttle programme roles within NASA were not well defined, so during the design process each Center attempted to carve out its niche of the business. The manifestation of struggles for proprietary control over technique, knowledge, expertise and even the artifact itself, was an intrinsic ingredient of technological development and change. Confrontation between the NASA Centers usually revolved around particular technologies or areas of technical knowledge. This process of negotiating jurisdiction boundaries around artifacts or facts among professional groups has been observed as a technique used to distinguish their work from others within similar fields.[42]

Members at Johnson tried to gain ownership of the programme by proposing a small interim shuttle that would serve as a test project for the larger version. Their strategy was simple; if successful, Johnson would have built up the necessary expertise to gain control over the

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41 James Thompson, ***Organizations in Action: Social Science Bases of Administrative Theory*** (New York, McGraw-Hill Book Co, 1967); Theo Farrell, ***Weapons Without a Cause***.

42 Anne Kerr, Sarah Cunningham-Burley, Amanda Amos, 'The New Genetics: Professionals Discursive Boundaries,' ***The Sociological Review*** 45, (May, 1997), pp 279-303.

development of larger shuttle at a later date.[43] Although NASA headquarters dismissed the idea, within its own ranks brewed another struggle between Dale Myers, Associate Administrator for Manned Space Flight (and former director of Rockwell) and Marshall's past director Wernher von Braun, who had been moved to a headquarters position. Each put forward ideas on phasing the shuttle programme, in the event of a funding shortfall. Myers, who through Rockwell had strong ties to Johnson, proposed an orbiter-first approach, whereas Von Braun, because of his allegiance to Marshall, favoured a booster-first approach.[44] Technical justifications were forwarded for both methods, but each was shaped by the perspectives and interests of the respective Centers. The coalition of interests was also pivotal in the building of the shuttle's main engines. Despite concerns voiced within NASA over the engine design proposed by Rocketdyne, the company was able to secure the resources to build it because of its close associations with Marshall.[45] Marshall, because of its expertise in the field of rocketry, also managed to persuade the Office of Manned Space Flight that the staged combustion engine

43 See chapter 3, fts 2-10.

44 See chapter 3, fts 12-25.

45 See chapter 5, fts 61-65.

design was superior to the gas generator, in spite of disagreement emanating from Johnson.[46]

Interests and goals thus crossed the social scale; nevertheless, they were, in themselves, shaped by the historical and structural conditions within which those that create them reside. The quest for space arose from the post-war economic boom, the escalation of the Cold War, and the growth of the technocratic state.[47] The shuttle was a product of these conditions, but it emerged during a period of transition. The history of the twenty years after 1973 is that of instability, crisis and the formation of a different role of government and state. The twin plagues of inflation and unemployment, brought forth the philosophy of the "free-marketeers", which advocated the rolling back of the state.[48] In parallel, the activities of science and technology were beginning to be viewed with suspicion and even trepidation. Protest grew in intensity and through environmentalism gained a platform to voice their concerns about the catastrophic potentials of scientific and technological progress.[49] For NASA, these shifts resulted in the shuttle becoming more closely aligned with the

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46 See chapter 4, fts 25-34.

47 Dale Carter, ***The Final Frontier***; Walter McDougall, ***The Heavens and the Earth***; John Logsdon, ***The Decision To Go To the Moon***; Noam Chomsky, ***American Power and The New Mandarins.***

48 Eric Hobsbawn, ***The Age of Extremes*** chapter 14.

49 Henry Bedford, ***Seabrook Station: Citizens Politics and Nuclear Power*** (Amherst, The University of Massachusetts Press, 1990); Colin Norman, ***The God that Limps.***

military. Although privatization did make the political agenda in the 1970s,[50] the redefinition of the shuttle as a national security asset best suited this change of ideological position.[51]

The above analysis has thus argued that social contexts were instrumental to the shaping of NASA's shuttle. However, to feature social contexts alone is insufficient. The shuttle was, above all, a physical artifact that had to work in the material world: a world that functioned independently from the human realm and frequently outside of its command. So it is worth noting Walter Vincenti's observation that:

> We should not, in our enthusiasm for social shaping (or construction) of technology, take ... technical shaping as incidental if we want to understand technological change in all its fascinating complexity.[52]

The shuttle builders could not decide which machines to build without some idea of how they were going to work. Hence, there must be some grounds for accepting that certain representations of the material world approach

50 See chapter 9, ft 6.

51 See chapter 8.

52 Walter Vincenti, 'The Technical Shaping of Technology: Real world Constraints and Technical Logic in Edison's Electrical Lighting System,' ***Social Studies of Science*** (August 1995), pp 553-574.

"reality"; for, as Serigo Sismondo has suggested, if they did not, then the world of representations would, in themselves, be autonomous of the material world that they aimed to explain.[53] In the fabrication of the shuttle both its form and performance had to *conform* to conditions produced by the material worlds within which it had to function. If conformity was not achieved then the technologies did not work. Thus, the actualization of technological potentialities had a propensity to stabilize around the physical processes involved in their functioning.[54] The choices available in design decisions were *constrained* by the material world: constraints that inexorably hemmed the engineers in; limited their room for manoeuvre; and reduced the possibilities. Ergo, material representations were important shapers of engineering solutions.[55]

A crucial part of engineering practice was the capture of material agency: the task of determining the conditions of "proper functioning." Design decisions concerning propulsion had to contend with the force of the Earth's gravitational pull. Together the boosters and the engines had to accelerate the shuttle to a velocity of over 17 000

53 Serigo Sismondo, ***Science Without Myth: On Constructions of Reality and Social Knowledge*** (New York, State University of New York Press, 1996), chapter 2.

54 Paul Dumouchel, 'Gilbert Simondon's Plea for a Philosophy of Technology,' Andrew Feenberg, Alastair Hannay, (ed) ***Technology and the Politics of Knowledge*** (Bloomington, Indiana University Press, 1995), pp 255-271.

55 Walter Vincenti, 'The Technical Shaping of Technology: Real world Constraints and Technical Logic in Edison's Electrical Lighting System,' ***Social Studies of Science*** (August 1995), pp 553-574.

miles per hour to overcome the Earth's gravitational pull and reach NASA's specified orbit.[56] Similarly, both the reaction control system and the orbital manoeuvring system had to produce *specific* delta velocities so that the shuttle could: be inserted into an orbital plane, maintain orbit, change its pitch, roll and yaw while in orbit, and be slowed down so that it would fall back to Earth.[57] For the designers, these criteria were unconditional. If they were not achieved then the technologies would not perform the required functions; they would not work. The material world, as represented by Newtonian physics, compelled the use of the rocket engine. This is not to say that the rocket engine will, for all time, be the sole method of propulsion able to reach and operate within space; just that when decisions were being made for the shuttle's propulsion systems, the rocket engine was the only solution to the problem of generating such high energy outputs.

The physics of getting to space also directed NASA and contractor engineers to reduce as far as possible, the shuttle's mass. For the main engines this meant a major change in structural design via a move away from bolts and flanges to welded constructions. On the external tank it drove the thickness of the aluminum walls. In the area of thermal protection, it was an important factor in the

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56 See chapter 4, ft 4.

57 See chapter 4, ft's 72, 82.

selection of a ceramic system over a metallic one. It was one of the primary reasons for the removal of the orbiter's jet engines.[58] Mass growth concerns also stripped the shuttle of many of the instrumentations required by Kennedy for ease of checkout and turnaround operations.[59] Nonetheless the possibilities of reducing total system mass were limited. State of the art in material technologies, structural design and fabrication techniques in the 1970s were not sufficiently advanced to offset all the problems of mass ratio. To launch more than just a rocket engine into space NASA had to adopt some form of staging technique, which is why all the shuttle configurations considered, had at least two separate stages. These, of course, are only a few examples, used to illustrate a general point. The relationships between, gravity, air resistance, momentum and mass, were so vital that almost every sub-system was shaped by them in some way.

Though the delta winged orbiter was essentially a design based on NASA's "need" to accommodate Air Force interests, it also became evident that the wing designers had to capture two kinds of physical forces, lift and drag; as well as profile the wing for optimum aerodynamic stability, control and manoeuvrability.[60] These criteria

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58 See chapter 4.

59 See Chapter 9, fts 55-60.

60 See chapter 4, fts 129-140.

were predominant shapers of the orbiter's wing and blended with the political decision to produce the delta configuration. Aerodynamic environments also played a pivotal role in shaping many of the shuttle's other sub-systems. For example, the length and diameter of the external tank, as well as the shape of its nose were all influenced by predictions of the aerodynamic loads produced during ascent. Furthermore, the configuration, surface and structural integrity of the thermal protection system were determined, to a large extent, by models in the aerodynamics and aerothermodynamics of reentry, as well as ascent.[61]

In each of these case, and in many others, both function and form had to comply with conditions produced by the material worlds within which the technology was to operate. Thus, a crucial element of engineering practice was the capture of material agency. It would be wrong to assume that the interplay between material agency and human agency followed a simple linear mechanism. The contours of the material world were not always fully known in advance: the shape of the machine, how it would perform, and the environment within which it was to operate, were continually being modified and explained through engineering and scientific practice. Problems invariably arose and their solutions had to be continually discovered.

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61 See chapter 7, fts 145-157.

Fabrication thus involved a 'dance of agency'; a dialectical interaction between the material and human worlds.[62]

The building of the shuttle's main engines provided a good illustration of this exchange between material an human agency.[63] Constant intervention was an inherent facet of engine construction. The original design failed to capture material agency successfully; it did not perform as intended. During fabrication and testing, the engine design threw up a myriad of different problems as various failures were exposed. Thus, the dance of agency was enacted. The parts were assembled, the machine was switched on, the engineers observed and monitored, and when the machine malfunctioned the engineers had to modify their understanding of how the engine worked, find solutions to the failures and then redesign and retest the machinery. Due to the complexity of the technology, however, the solutions were not always apparent; the machine did not give up its inner workings easily. Failures tended to reappear and/or become redefined; and in the case of the turbo-machinery, eventually become accepted as an innate aspect of the design.

The shuttle's main engines were not, however, an isolated example. In every case detailed, the technology

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62 Andrew Pickering, ***The Mangle of Practice: Time, Agency, and Science*** (Chicago, The University of Chicago Press, 1995).

63 See chapter 7, fts 33-84.

never functioned as expected, nor did the predictions or models of the material world remain completely fixed. Far from being an un-problematic progression of design, development and operation, the formation of the shuttle was a messy practice strewn with intricacy and uncertainty. The actors involved in its fabrication often ventured into unknown territory, and as they did so, their activities embraced many possible scenarios. Social values then can also surrounded the *meaning* of the shuttle. The "detailed facts" about its workings, can in themselves be seen as social constructs. Disparate interests, opposing knowledge claims, dispute and controversy often resulted in a seemingly unambiguous thing becoming several different things at once, dependant upon a multiplicity of human "viewpoints". What, on the surface, appeared as a solid or fixed object was frequently open to "interpretative flexibility", where a variety of interpretations formed around the purpose of the technology or about its functioning. For different social groups the shuttle as a whole and in its parts, housed radically different meanings.[64] This fluidity of interpretation was especially pronounced during technological testing.

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64 Ronald Kline, Trevor Pinch, 'Users as Agents of Technological Change: The Social Construction of the Automobile in the United States,' ***Technology and Culture*** (October 1996), pp 763-795; Wiebe Bijker, 'Do Not Despair: There is Life After Constructivism,' ***Science, Technology and Human Values*** (Winter 1993) pp 113-118; Trevor Pinch, 'The Social Construction of Technology: A Review,' Robert Fox, (ed) ***Technological Change: Methods and Themes in the History of Technology*** (Netherlands, Harwood Academic Publishers, 1996), pp 17-35; John Law, Michel Callon, 'The Life and Death of an Aircraft: A Network Analysis of Technical Change,' Wiebe Bijker, John Law, (ed) ***Shaping Technology/Building Society: Studies in Sociotechnical Change*** pp 21-52; Weibe Bijker, 'The Social Construction of Fluorescent Lighting, or How an Artifact was Invented in its Diffusion Stage,' Wiede Bijker, John Law, (ed) ***Shaping Technology/Building Society: Studies in Sociotechnical Change*** pp 74-102; Kann Garrety, 'Social Worlds, Actor-Networks and Controversy: The Case of Cholesterol, Dietary Fat and Heart Disease,' ***Social Studies of Science*** (October 1997), pp 727-73.

Testing performs a vital role in the development, fabrication and operation of technology. It establishes whether a concept is feasible by revealing faults within the design; it forms a general confidence that the technology will work within its functioning environment; and it certifies that the technology will work consistently over a specified amount of time. Testing is thus the formal method of specification and identification of how the technology will perform, is performing, or has performed.[65]

In technically complex projects, like the shuttle, many different groups of engineers are involved in the testing processes. All the components are, at first separated and tested in isolation, before being integrated into the system as a whole. As with other elements of the programme, therefore, testing was a process of negotiation: between groups of engineers, between engineers and managers, and between the engineers and the technology. The shuttle engineers pushed for the maximum technical performance from the components for which they were responsible. This frequently resulted technical problems and failures. Thus, during testing, the technical specifications were open to negotiation. Development of the shuttle's main engines is a good example of this process in action. Modification of the hardware was not the only

65 Trevor Pinch, 'Testing - One, two, Three ... Testing!: Towards a Sociology of Testing,' ***Science, Technology, and Human Values*** (Winter, 1993), pp 25-41.

action to result from the emergence of failures during the testing process. The specifications of many of the components were also changed. The design goal 27 000 seconds running time could not be obtained with either the turbine blades or the engine nozzle and both were reduced to 5 000 seconds and 12 000 seconds respectively. Indeed, because of these problems and others, the engine design life was reduced to 15 000 seconds running time: a major change of systems design, which had an adverse impact on the number of flights and, therefore, on the justifications of the programme as a whole.[66]

Pickering see this "goal modification" as part of the dance of agency. He argues that goals emerge from practice: that machines serve as the surface of emergence for the goals of practice and, therefore, human intentions. Thus, a crucial part of building machines is the process of "tuning" in which goals are transformed and "dictated" too by the functioning of the machine. In the struggles with material agency, plans and goals are always liable to revision.[67] Examples of this process of tuning are scattered throughout the shuttle's history. As knowledge about the "actual" functioning of the machines was constructed, negotiation about the goals of the parts, and the whole, followed.

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66 See chapter 7, fts

67 Andrew Pickering, ***The Mangle of Practice***

The shuttle's main engines also provide a good example of another dimension to testing: that of replication. In chapter 7 it was shown that the engineers had to modify their testing practices from constructing theoretical models of how the engine worked to building up empirical knowledge from hardware failures. However, because of the integrated nature of the engine, the location of failure, or the cause, was not always possible to find and, thus, relied on engineering judgement about how the engine worked. Continuous problems with the valves, bearings and the pumps illustrate this well. Solutions to the initial failures were implemented, the engines were tested again, they appeared to work, but then failed again at a latter date. Determining the cause of failure was thus a complex matter: especially when the failure did not occur with regularity. Problems with the engines heat exchanger also highlighted the difficulty of replication. A fire in one engine was believed to be caused by a leak in the heat exchanger, but in isolated tests on the component the engineers could not replicate the failure and, therefore, not determine the cause. It was not until two years later that they discovered Rocketdyne had been constructing the part from "below specification" materials. The heat exchangers that the engineers had been testing were not the same as the one on the engine itself.

Confidence that the shuttle would work was reached gradually, through a succession of "successful" tests taken together. However, the knowledge accrued through testing was invariably open to dispute and the value of the results, and the accuracy of the measurements, were often open to question.[68] The discussions on eliminating the obiter's jet engines, detailed in chapter 4, was one such controversy. Those within NASA that suggested the move, were confident that the orbiter could land safely without jet engines because of their past experiences with bringing spacecraft back to Earth. Others, however, questioned these judgements. Bringing a space capsule back down to land in ocean, within a 200 mile radius target, was a lot different from landing an orbiter on a mile long runway strip.

Similarity relationships and similitude requirements, thus, lay at the heart of testing.[69] Depending on the operational environment, certain tests could only be accomplished through the use of scale models in artificial conditions created from theoretical assumptions, empirical knowledge, engineering judgement and a reliance on instrumentation. Some subsystems, therefore, did not undergo an "actual test" until the shuttle flew as a whole for the first time. Thermal protection and aerodynamic design both fell into this category. The arc tests on the

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68 Donald MacKenzie, 'From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy,' David Gooding, Trevor Pinch, Simon Schaffer, (ed) ***The Use of Experiment: Studies in the Natural Sciences*** (Cambridge, Cambridge University Press, 1989).

69 ***Ibid;*** Donald MacKenzie, 'How do we Know the Properties of Artifacts? Applying the Sociology of Knowledge to Technology,' Robert Fox, (ed) ***Technological Change***; Trevor Pinch, 'Testing - One, two, Three ... Testing!: Towards a Sociology of Testing,' ***Science, Technology, and Human Values*** (Winter, 1993), pp 25-41; Walter Vincenti, ***What Engineers Know and How They Know It*** especially chapter 5.

thermal protection system, although an indicator of heat resistance, did not represent the total operational environment through which the system had to work. In addition to the arc tests, NASA's engineers had to simulate the complex air flows of reentry: the most difficult of which was boundary-layer transitions from laminar to turbulent flows. Recreating turbulent flows in the laboratory was not an easy task, because of their chaotic nature. Similitude requirements were, therefore, difficult to meet and the "validity" of results depended upon the acceptance of the engineering community about the claims of the similarity relationship. This acceptance only came after controversy. There was a concern within NASA that the sheer amount of data coming from the wind tunnel tests and computer models was hindering the analysis. Only after a minor investigation by senior management was confidence restored.[70]

Negotiation about the operational environment was, therefore, a pervasive part of the testing process. Results accrued through one set of tests did not always correspond with results from another set of tests. This could be clearly seen with the contention that arose about the structural integrity of the thermal protection tiles. Confidence in the tile systems was in serious doubt after "refined" aerodynamic and aerothermodynamics data indicated

70 See chapter 7, fts 114-135.

that the reentry and ascent environments were far more severe that the tiles had been designed for. The "pull-test", initiated by Kennedy, were an attempt to restore this confidence, but the final result was a major redesign of the tiles.[71]

Above I discussed the impact of material agency on the shaping of the technology. However, the influence of material agency reaches beyond the shaping of technical matters. Synchronous with technological change is social change. Large, complex technologies, like the shuttle, are not just simple tools that can be introduced without wider social consequences. In their modes of operation, gargantuan sociotechnical assemblages require changes in human practice, philosophy, culture and politics.[72] The operation of the shuttle stood in direct opposition to the way NASA had originally been organized, and the way in which that organization had worked.[73] NASA's members had to adapt to a new environment that stressed routine and economic operations in space. In effect, the shuttle

71 See chapter 7, fts 140-156.

72 Mesthene Emmanuel, ***Technological Change: Its Impact on Man and Society*** (Cambridge, Massachusetts, Harvard University Press, 1970); Robert Heilbroner, 'Do Machines Make History?' ***Technology and Culture*** (July, 1967); William Ogburn, ***On Culture and Social Change: Selected Papers*** O. Duncan, (ed) (Chicago, The University of Chicago Press, 1964).

73 See chapter 9

reprogrammed its environment to suit the special conditions of its own operation. Reusability, hardware life and turnaround procedures, were all new to NASA. Together they influenced a change in philosophy and practice, especially at Kennedy. Whereas all of NASA's previous launches could all be treated unique events, the shuttle necessitated standardization and uniformity: a production line approach that emphasized costs and schedule.

In the process of planning and preparation for the shuttle's operational phase, NASA attempted to emulate the commercial airliners mode of operations. Although unsuccessful, what this led to was an impression that the shuttle would operate like a commercial airline. Many within NASA were unconvinced, and when Columbia finally arrived at Kennedy, it confirmed for them that the shuttle was going to be anything but routine. The "reality" and the "myth" collided. This collision led to the growth of antagonism between managers and engineers. NASA's higher echelons, for political reasons, were pushing to get the cost-per-flight down, which meant raising the amount of flights per year and standardizing the turnaround process. However, NASA and contractor engineers were primarily concern with the physics of failure. Their engineering culture dictated that they had to know why each failure occurred, no matter how small, and eliminate its cause. In addition, NASA's engineering culture embraced a penchant for improvement. NASA's administrators, thus, had difficulty in stopping the engineers from "tinkering" with the machine. The new technology, then, did not totally dominate. NASA's existing culture and practices continued in friction with the machine's operational requirements.

Technology's impact on the sociotechnical order, however, also occurred prior to any use and long before the machine was put into operation. It took place as a consequence of fabrication. Once an individual, organization or artifact was incorporated into the sociotechnical assemblage, it was restructured to conform to its modes of practice; it became an active part of the entire system.[74] Hence, social change occurred at the start of technological creation, because the very activity of design, development and fabrication entailed the organization of people and things in a specific form. Chapter 5 detailed some of the organizational and management changes that occurred at the start of the shuttle's development. As was shown, NASA's upper management considered that the character of the shuttle was very different from that of Apollo, so required a different type of management structure. During Apollo the spacecraft and the booster were treated with equal importance and the organizational structure reflected that. With the arrival of the shuttle, the orbiter (spacecraft) rose in status to

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74 Langdon Winner, ***Autonomous Technology: Technics-out-of-Control as a Theme in Political Thought*** (Cambridge, Massachusetts, MIT Press, 1978); Herbert Marcuse, ***One Dimensional Man: Studies in the Ideology of Advanced Industrial Society*** (London, Routledge & Kegan Paul Ltd, 1964).

stand above the booster. The reason behind this was the technical nature of the orbiter: a far more complex system than NASA had ever built before, the orbiter's development required an intricate means of control over sub-systems integration. Systems integration, thus, went hand in hand with orbiter development and fabrication. What this effectively translated into was Johnson, the Center in charge of the orbiter, and Rockwell, the contractor selected to build the orbiter, taking overall control of the programme.

With increased complexity, however, comes the possibility of a 'crisis of control'.[75] The problem of "autonomous" technology lies in the understanding of complexity. Complexity and the uncertainty that arises from it has been described as the 'soul' of technology.[76] Specialization and fragmentation entailed the concentration of expertise at the level of the sub-system. Hence, because of the millions of interlocking parts, no one person or constituency had an absolute understanding of how the technological system worked as a whole. The members of the technological order only had a *limited* knowledge of their artificial environment. The higher echelons of the sociotechnical assemblage thus entrusted the particulars to the lower echelons and the lower echelons credited the

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75 Thomas Hughes, 'Managing Complexity: Interdisciplinary Advisory Committees,' Robert Fox, (ed) ***Technological Change*** pp 229-245.

76 Langdon Winner, ***Autonomous Technology***.

highest with an understanding of the universal. Each, however, deceived the other. The goals of the assemblage's elite could only be realized through the collective cooperation of its lower levels, who were primarily concerned with the preservation of their own objectives.[77]

What this reconstructed history has clearly shown then, is that technological development and change does not follow a predictable or "natural" path; nor is it the result of a unilinear exchange between science and technology. Technological change is diverse, unpredictable and contradictory. In the creation this large technological systems a variety of organizations, individuals and things were enrolled into a range of associations, which were continually being enacted and reenacted. The composition, function and purpose of the sociotechnical assemblage was not fixed, but dynamic. Intended and unintended consequences, domino effects, and uncertainty were all part of design, development, fabrication and operation process. Indeed the technology and the social organization were so complex that the most interesting thing about the shuttle's history is not that the machine failed, as in the case of Challenger, but that it actually worked at all.

[77] See chapter 5, fts 74-88; chapter 9, fts 28-29, 60-64.

Appendix 1

Glossary[1]

Angle of Attack:

The angle between a reference line fixed with respect to an airframe and a line in the direction of movement of the aircraft.

Attitude:

The position or orientation of an aircraft, spacecraft, or other object, either in motion or at rest, as determined by the relationship between its axes and some reference line or plane.

Azimuth:

True launch heading measured clockwise from 0 degrees north.

Boil-off:

Cryogenic fuels have very low boiling points and must be kept extremely cold to avoid evaporation. It is the loss of these fuels through evaporation that is know as boil-off.

Centre of Gravity:

The point at which the entire weight of a body may be considered as concentrated so that if supported at this point the body would remain in equilibrium in any position.

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1 Sources: ***McGraw-Hill Encyclopedia of Science and Technology*** (New York, McGraw-Hill Book Co, Fifth Edition, 1982); Sykes J.B. (ed) ***The Concise Oxford Dictionary*** (London, Guild Publishing, Seventh Edition, 1982); Berger Stanley. ***Laminar Wakes*** (New York, American Elsevier Publishing Company Inc, 1971); Etkin Bernard. ***Dynamics of Flight: Stability and Control*** (New York, John Wiley & Sons Inc, Second Edition, 1982); Kermode A.C. ***An Introduction to Aeronautical Engineering: Vol 1, The Mechanics of Flight*** (London, Sir Issac Pitman & Sons Ltd, 1940); Morita W.H. (ed) ***Space Shuttle System Summary*** (Rockwell International, Space Systems Group, SSV80-1, May 1980); Reagan Frank. ***Re-entry Vehicle Dynamics*** (New York, American Institute of Aeronautics and Astronautics Inc, 1984); Vincenti Walter. ***What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*** (Baltimore, The John Hopkins University Press, 1993); Dutton Lyn. de Garis David. Harding Richard. ***Military Space*** (London, Brassey's UK, 1990); GAO. ***Space Transportation Systems: Past, Present, Future*** May 27, 1975 (General Accounting Office Distribution Center, Washington DC); Gray Mike. ***Angle of Attack: Harrison Storm and the Race to the Moon*** (New York, London, W.W. Norton & Company, 1992).

Dynamic Instability:
A complicated phenomenon in which a body oscillates about its equilibrium condition with ever-increasing amplitude.

Elevon:
A control surface which acts like a combination of an aircraft elevator and aileron, controlling pitch and roll.

Empennage:
An arrangement of stabilizing surfaces on the tail of an aircraft.

Flange:
A radially projecting or flat collar, or rim, used to strengthen an object or attach it to another object.

Hypersonic:
Refers to speeds above Mach 5; five times the speed of sound.

Lift/Drag Ratio:
Lift is what keeps an aeroplane in the air. To obtain lift the wing must be propelled through the air at a definite velocity and it must be set at a definite angle of attack to the flow of air past it. Wing shape and angle of attack, therefore, determine the lift coefficient. Lift can only be obtained however, at the expense of a certain amount of drag. This relationship can be plotted and is known as a lift/drag ratio curve.

Mach:
The term used to describe the speed of objects relative to the speed of sound.

Mach Number:
In fluid mechanics the Mach number is defined as the ratio v/c of the free stream velocity, v, to the velocity of sound, c, in the fluid at the same conditions, such as temperature and pressure. Mach number is also the ratio of the inertia force of the fluid to the force of compressibility. A body moving through the fluid at subsonic speeds is preceded by a region of gradually varying density and pressure that controls the flow around the body. At Mach numbers equal to or greater than unity the gradual transition of pressure cannot exist and shock waves form at critical sections on or near the surface of the body and extend outwards.

Manifold:

A chamber or pipe that contains a number of inlets and outlets to distribute fluid and gases to and from an engine.

Mass Ratio:

A design parameter, which relates to the total mass of a launch vehicle at ignition over its final mass at burn-out.

POGO:

A situation of coupled oscillations between a vehicle propellant feed system and the propulsion system.

Nautical Mile:

A unit of distance used principally in navigation. Equal to 1.15 statute miles.

Near-Earth-Orbit:

Generally considered to be between 100 and 400 nautical miles, while far-earth-orbits reach out to 1000 nautical miles or higher.

Payload:

A specific complement of instruments, space equipment and support hardware carried aloft to accomplish a mission or discrete activity in space.

Prandtl-Meyer Expansion Angle:

Related to the Prandti-Meyer expansion fan, which is a steady planar compressible fluid flow that occurs only at supersonic speeds.

Regenerative cooling:

A rocket engine cooling system which comprises of a jacket around the combustion chamber and nozzle through which one of the propellants (liquid hydrogen or liquid oxygen) is pumped through passages in the jacket to keep the combustion chamber walls cool. The heat absorbed by the coolant is ultimately injected back into the chamber.

Reynolds number:

The Reynolds number is defined as $Re= UL/v$, where U is the free-steam speed, L a characteristic length of the body and v is the kinematic viscosity. The Reynolds number is significant in the design of any system in which the effect of viscosity is important in controlling the velocities or the flow pattern.

Specific Impulse:

Specific impulse is defined as the thrust produced per unit of mass of propellant per second.

Subsonic:

Relating to speeds less than that of sound.

Supersonic:

Relating to speeds greater than that of sound.

Torque:

Any force that causes rotation.

Transpirational cooling:

A rocket engine cooling system in which cooling is accomplished by layering a film of coolant (liquid oxygen or liquid hydrogen) along the surface of the combustion chamber and nozzle. Disruptions in the film are renewed by injecting more coolant to reform the film.

Trim:

The attitude of an aircraft in flight when a pilot allows the main control surfaces to take up their own positions.

Appendix 2
List of Informants

Abrahamson. James A. *NASA Associate Administrator. Lieutenant General, USAF.* (Washington DC: July 5, 1995).

Beddingfield. Samuel T. *NASA, KSC Deputy Director Space Shuttle Projects Management.* (Titusville, Florida: July 31, 1995).

Beggs. James M. *NASA Administrator.* (Virginia: June 6, 1995).

Bethay. Woody. *NASA, MSFC Associate Director.* (Huntsville, Alabama: August 24, 1995).

Carey. Ted. *Rockwell.* (Titusville, Florida: July 22, 1995).

Chaffee. Norman. *NASA, JSC, Chemical Engineer.* (Houston, Texas: September 6, 1995).

Cohen. Aaron. *NASA, JSC Director* (College Station, Texas: September 8, 1995).

Day. LeRoy E. *NASA. Director at Office of Manned Space Flight.* (Rockville, Maryland: June 26, 1995).

Donlan. Charles. *NASA. Deputy Associate Administrator for Manned Space Flight.* (Washington DC: June 7, 1995).

Dupree. Raymond D. *Rockwell.* (Huntsville, Alabama: August 21, 1995).

Edelson. Burton I. *NASA. Associate Administrator for Science and Applications.* (Washington DC: June 22, 1995).

Ellis. Larry. *NASA. KSC, Space Shuttle Operations.* (KSC, Florida: July 27, 1995).

English. George. *NASA. KSC, Management Systems Officer.* (Cocoa Beech, Florida: July 26, 1995).

Faget. Maxime. *NASA. JSC, Manager or Engineering and Development.* (Houston, Texas: September 9, 1995).

Fleming. Bob. *NASA. KSC, Manager for Overseas Emergency Landing Sites.* (KSC, Florida: July 25, 1995).

Frietag. Robert. *NASA. Deputy Director of the Advanced Programs Office, Office of Manned Space Flight.* (Annandale, Virginia: June 5, 1995).

Halsema. John. *NASA. KSC, Workforce Management and Industrial Relations Office.* (KSC, Florida: July 26, 1995).

Hello. Bastian. *Rockwell. Space Shuttle Program Manager.* (Rockville, Maryland: April 27, 1995).

Hoban. Francis. *NASA. Executive Assistant to the Deputy Administrator.* (Fairfax, Virginia: May 15, 1995).

Jackson. James. *NASA. KSC, Integration Management.* (KSC, Florida: July 12, 1995).

Kingsbury. James E. *NASA. MSFC Director of the Science and Engineering Directorate; External Tank Manager.* (Huntsville, Alabama: August 16, 1995).

Kline. Richard. *Grumman Aerospace. Space Shuttle Program Manager.* (Washington DC: May 31, 1995).

Kraft. Christopher. *NASA. JSC Director.* (Houston, Texas: September 1, 1995).

Lee. Chester M. *NASA. Director of STS Operations; Director of STS Customer Services.* (Arlington, Virginia: May 2, 1995).

Leinbach. Michael D. *NASA. KSC, Chief, Test Director's Office.* (KSC, Florida: July 27, 1995).

Lindstrom. Robert. *NASA. MSFC, Space Shuttle Program Manager*. (Huntsville, Alabama: August 17, 1995).

Mark. Hans. *NASA. Deputy Administrator. Secretary of the USAF.* (Austin, Texas: September 8, 1995).

McCartney. Forrest. *NASA. KSC Director. Lieutenant General, USAF.* (Cape Canaveral USAF Base, Florida: July 28, 1995).

Nagel. Conrade. *NASA. KSC, Shuttle Flow Director.* (KSC, Florida: July 25, 1995).

O'Conner. Bryan. *NASA. Deputy Associate Administrator, Space Shuttle.* (Washington DC: May 7, 1995).

Odem. James. *NASA. MSFC Director of the Science and Engineering Directorate; External Tank Manager.* (Huntsville, Alabama: August 21, 1995).

Sieck. Robert. *NASA. KSC, Director of Shuttle Operations.* (KSC, Florida: August 1, 1995).

Sneed. Bill. *NASA. MSFC, Shuttle Program Planning and Control.* (Huntsville, Alabama: August 21, 1995).

Solid. Lee. *Rocketdyne.* (KSC, Florida: July 26, 1995).

Stever. Guyford. *Chairman, Panel on Technical Evaluation of NASA's Redesign of the Space Shuttle Solid Rocket Booster, National Research Council; Presidential Science and Technology Advisor.* (Washington DC: June 7, 1995).

Talone. Tip. *NASA. KSC, Shuttle Flow Director.* (KSC, Florida: July 25, 1995).

Thompson. Robert. *NASA. JSC, Space Shuttle Program Manager.* (Houston, Texas: September 9, 1995).

Tischler. Adelbert O. *NASA. Director Chemical Propulsion Div, Office of Advanced Research and Technology; Director of Low Cost Systems Office.* (Washington DC: May 3, 1995).

Tribe. John. *Rockwell. Chief Engineer.* (KSC, Florida: July 28, 1995).

Truly. Richard. *NASA Administrator.* (Atlanta, Georgia: July 11, 1995).

Uman. Myron F. *Project Director, Panel on Technical Evaluation of NASA's Redesign of the Space Shuttle Solid Rocket Booster, National Research Council.* (Washington DC: April 24, 1995).

Yarbrough. Herb. *NASA.* (Houston, Texas: September 5, 1995).

Yardley. John F. *NASA. Associate Administrator for Space Transportation System; President of McDonnell Douglas Astronautics Co.* (St Louis, Missouri: August 9, 1995).

Webb. Jenny. *NASA. KSC, Shuttle Flow Director.* (KSC, Florida: July 25, 1995).

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